Filtering DDoS traffic using the P4 programming language

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ABSTRACT

To counter the growing problem of DDoS attacks, the availability of prevention and mitigation tools is important. Currently most of those tools are expensive in software and/or hardware. Open source solutions are very limited in both availability and functionality. The P4 programming language may be used as a step in the right direction. The language is platform independent and can thus be used to run the same code on several hardware components. This makes it a good platform for wide-scale open-source development of DDoS protection tools. The usefulness of P4 for filtering DDoS packets is analysed by assessing how known filtering methods could be implemented in P4 and by implementing one of the methods, History-Based IP filtering (HIF), and documenting the problems and limitations. It turns out that P4's lack of loops, the reliance on control-plane for filling match-action tables and the limited storage facilities of registers are the main limitations. However, despite these limitations, simpler filtering mechanisms can be implemented or already have open source implementations. The P4 implementation of HIF, is shown to drop 99.87% of DDoS packets. However, it also drops about 10.19% of legitimate traffic.

Keywords

DDoS, P4, filtering, BMV2, software switch, History-based IP Filtering, HIF

1. INTRODUCTION

With the steady incline in rate and severity of Distributed Denial of Service (DDoS) attacks [9], the need for defence mechanisms against those attacks grows. There are two main types of defence mechanisms, firstly prevention and secondly detection and mitigation.

Prevention uses techniques that are in place before any attack happens. Examples of this are *over provisioning* and *modifying scheduling algorithms* (e.g. ordering traffic according to the amount of suspicion). The detection and mitigation mechanism tries to detect when a DDoS attack is happening and reacts accordingly. The first part of this mechanism, detection is concerned with determining whether a system is being attacked. To mitigate such an attack multiple tactics can be used, for example, rate-limiting and filtering. Rate limiting means that a fraction of the packets is dropped either at the end server, or somewhere upstream, in order to reach manageable numbers. Filtering seeks to eliminate attack traffic, while keeping the normal traffic. [20]

Even though companies dedicated to DDoS mitigation are capable to handle most DDoS attacks, most small companies have neither the right knowledge for development of mitigation systems, nor the funds to buy off the shelf products or services. Even though there is a lot of research available on this topic, there are not a lot of open-source tools that can be deployed [12].

The P4 language (Programming Protocol-independent Packet Processors) [11] could be used as a platform to facilitate the development of efficient open-source tools for this domain. This programming language is designed to be target independent (i.e. suitable for describing everything from high-performance forwarding ASICs (Application-Specific Integrated Circuits) to software switches [6]) and is therefore suitable for wide-scale open-source deployment.

P4 is already rapidly rising in popularity, according to [14] the P4 Language Consortium boasts over 12 university members and 44 industry members, including companies such as Microsoft, Intel, Cisco, and VMWare. SIGCOMM 2016 included five papers related to P4. Using P4, developers have created a variety of powerful new applications including advanced network diagnostics and telemetry and responsive traffic engineering.

1.1 Objective

The goal of this research is to evaluate how suitable P4 is for the implementation of filtering techniques. To this end several filtering techniques are explained and discussed to determine how they can, or can not be implemented in P4. In addition, a filtering technique is selected in section 3.2 based on the requirements listed in section 3.2.1. This filtering technique is implemented and verified to assess the correctness of the implementation.

This verification will be both qualitative and quantitative. The qualitative part will consist of determining if the filtering works as expected, i.e. DDoS related packets are filtered and normal packets are passed to some extent. The quantitative part will consist of measurements of the rates of the filtering mechanism that are described in table 1.

The results of this research are a starting point for developers of state-of-the art open-source DDoS protection tools in P4. These tools could then be used by any company to make their services more resilient against these types of attacks and thereby increase the reliability.

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Table 1: Performance measurement rates

Name	Description
True drop rate	The percentage of DDoS packets that is dropped during the test.
False drop rate	The percentage of normal packets that is dropped during the test.
False pass rate	The percentage of DDoS packets that is passed during the test.
True pass rate	The percentage of normal packets that is passed during the test.

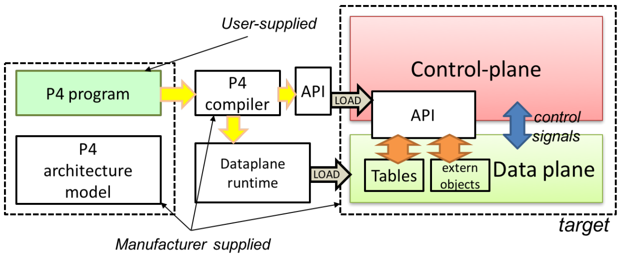

Figure 1: Programming a target with P4 [8]

2. BACKGROUND

2.1 The P4 language

P4 is set in the context of Software defined Networking (SDN). SDN aims to give operators more control by separating the control plane from the data plane or forwarding plane. P4 is designed to program the data plane of forwarding devices in a way that is target-independent, so that the same code can run on multiple hardware devices; and protocol-independent so that switches programmed in this language are not tied to specific protocols. [11] However, P4 programs do depend on the architecture of a device. This architecture has to be described by the manufacturer in the form of a P4 specification [8]. The forwarding planes can use common interfaces like OpenFlow so that they can be configured by existing control plane software [11].

The main benefit of P4 is that it provides more flexibility for the expression of forwarding policies. This in contrast to traditional switches which provide fixed-function forwarding engines [8].

2.1.1 *Features*

The most recent version of P4 is $P4_{16}$. This section describes a relevant subset of the current feature-set of P4 and how those relate to filtering techniques. For the full specification, see [8].

As can be seen in fig. 1, a P4 program builds on a manufacturer supplied P4 architecture model. When it is compiled, a data plane runtime and API is generated. The data plane code is used to control the data plane or forwarding plane of the switch, while the API is used by the control plane to communicate data with the data plane.

The basic structure of a P4 program includes the following elements.

Parser Extract the necessary headers from packets.

Match-Action pipeline Match keys, which are derived from the packets or metadata, to actions using tables and execute the actions. This matching can be done exactly, based on a pattern (ternary) or based on the longest prefix.

Deparser Insert (edited) headers back into the packet.

A program may include multiple elements of these types. The elements are always executed in this order, first the parsers, then the Match-Action pipelines finally the deparsers.

Like other programming languages P4 also has statements and expressions, these can be used in control blocks, action blocks and parser states. These statements include variable declarations and assignments, calls to actions. Actions in P4 can be compared to functions in other languages, they have input and output arguments and can perform statements.

One of the limitations of P4 is that there are no loop constructs, this is to keep a bound on the computation time for each packet. The expressions include the usual comparisons and arithmetic operations. However, P4 does not include floating point numbers.

A P4 program follows the flow of a program through the application, therefore if no packet is being processed, no tasks can be done from the forwarding plane.

2.1.1.1 *Data storage and retrieval.*

There are several ways in which a P4 program can store data. Some of these storage elements are only available for the current packet, such as user-defined metadata, packet headers and local variables. Other elements are available across packets, such as registers, counters and meters, these objects are provided by the architecture using the *extern* construct.

Registers are similar to arrays in other programming languages. They have a predefined number of slots which can be used to store one of the base types, match_kind, bool, integer [8]

The match-action tables are a special type of storage elements since P4 programs cannot store data in them, however, they can read the data that is stored in the tables by the control plane. These tables can be used to store data necessary for filtering, however, if that data needs to be collected from packets, this means that for every packet a message should be sent to the control plane, after which the control plane fills the match-action table. This generates a considerable overhead which denies the performance benefits of using P4 for this task instead of higher level filtering devices.

For some types of filtering mechanisms timestamps are necessary, those can be obtained from the *standard_metadata* fields *ingress_global_timestamp* and *egress_global_timestamp*. This *standard_metadata* also includes other useful fields like ingress and egress ports for routing, a drop flag and packet length.

2.2 BMV2 software switch

The P4 capable device that is used for testing during this research is the BMV2 software switch [1]. A software switch is a switch that is simulated in software, this in contrast to a normal switch that is implemented in hardware.

2.2.1 *Communication from control plane to data plane*

To communicate with the data plane of the BMV2 switch there are two main methods, namely P4 runtime [3], which uses a GRPC [3] interface, and the BMV2 CLI. P4 runtime has the benefit that it is more scriptable, however, it lacks some features, like writing registers, that the CLI does have. Because register writing is a feature that is necessary for the implementation described in section 4, the CLI is used during this research.

2.3 DDoS attacks

DDoS attacks can be categorised into two categories, bandwidth depletion and resource depletion. Both categories aim to prevent legitimate communication with the server. They do this in different ways. Bandwidth depletion attacks achieves this by getting packets dropped because there is not enough bandwidth. Resource depletion attacks achieves this by sending requests that require some processing by the server, thereby they keep the server busy with the attack packets with the effect that it does not respond to legitimate packets. A frequently used technique in DDoS attacks is IP spoofing [19], (i.e. packets are sent with a different IP source address than the actual source). Out of the 18 types of attacks analysed by [17] 11 use some form of IP spoofing.

3. FILTERING

Filtering is one of the methods used to mitigate DDoS attacks. It can be applied at several places in the network, at the source (source-initiated), somewhere along the path (path-based) or at the destination (victim-initiated). When using source-initiated filtering, sources filter their own output to make sure that no attack traffic is sent. Examples of this category are *Egress filtering*, *Martian address filtering* and *Source address validation*. In path-based filtering nodes along the path of a packet drop packets that follow a wrong path. An example of this category is Route-based packet filtering (RPF). In victim-initiated the traffic that arrives at the victim is filtered, or the victim tells upstream to reduce the traffic. Examples of this category are *Confidence-Based filtering (CBF)*, *History-Based IP filtering (HIF)*, *Hop-count filtering (HCF)*, *PacketScore*, *Path identifier (Pi)* and *Signature-based filtering*. [16] Another division can be made on whether the algorithm uses a detection mechanism to switch states or filters continuously. The continuously filtering techniques are *Ingress/egress filtering*, *Martian address filtering*, *source address validation*, *RPF*, *Pi* and *Signature-based filtering*. The filtering techniques that need detection are *HCF*, *HIF*, *PacketScore* and *CBF*.

3.1 Techniques

This section describes commonly used filtering techniques and their suitability for implementation in this research according to the requirements set in section 3.2.1.

3.1.1 Ingress/egress filtering

Ingress filtering drops packets with spoofed IP addresses by only allowing a predefined range of IP addresses into the network.

Egress filtering drops packets that are leaving a subnet but do not have a valid source IP from that network.

The success of these techniques depends on if the range of valid IP addresses is known, which is not always the case. Also, attackers can spoof IP addresses in such a way that they are still within the valid range. [17] These types of filtering are easily implemented in P4 because they require only table lookups. And the table entries do not depend on the received packets, so no communication is needed from data plane to control plane. They have been implemented in [21].

3.1.2 Martian address filtering and source address validation

Martian address filtering drops packets with reserved or invalid source IPs. This prevents attackers from randomly spoofing packets.

Source address validation drops packets that arrive on a different port than where a packet would be routed when returned to the sender. In other words, if an address is never reached over a specific port, no packets should be received from that address over that port. A drawback of this technique is that it yields many false positives for asymmetric routes. Another drawback is that not all routers in the internet implement this, so it is currently not effective [17]. These filtering techniques are defined in RFC 1812 [10]. They have been implemented in [21].

3.1.3 Route-based packet filtering (RPF)

This filtering technique filters using the principle that each link of a core router accepts traffic from only a limited number of source addresses. This way the network topology can be used to drop packets that have an incorrect source for their destination. Significant success of this technique will be achieved if 18% of the autonomous systems implement this filtering technique. This amount is impractical to realise considering how the internet is structured currently. To include the source address in a BGP message, the format has to be adapted. This results in bigger BGP message size and longer processing times of these messages. Attackers can bypass this filtering technique by choosing spoofed IP addresses in such a way that they are not detected. [17] For an implementation in P4, the source IP address and link of the core router can be used as keys to a match-action table, in which the accepted combinations can be saved by the control plane. An implementation on a single device is hard to test since the amount of packets that is filtered per device is very low, several routers are necessary to achieve a good accuracy.

3.1.4 Hop-count filtering (HCF)

This filtering technique uses the TTL value to determine how many hops a packet has travelled. It calculates this hop count by subtracting known initial TTL values (30, 32, 60, 64, 128, 255) from the received TTL. Sometimes there are multiple possible initial values, then values for the different possible initial values are saved. It uses this value to determine if an source IP address is likely to have been spoofed by comparing the values of received packets with the saved values.

It has two states, *alert* and *action*. The alert state is the normal state, during this state no packets are dropped even if they are detected to be spoofed, this prevents collateral damage. The action state is entered when a DDoS attack is detected, during this state all packets with an incorrect hop count are dropped. To determine this expected value an IP to hop count mapping is created during the alert state. This technique can recognise close to 90% of spoofed IP packets. [15] This can drop packets with spoofed IPs because those packets often also have invalid hop counts. However, this technique has the drawback that the number of false positives is high. [17] For implementation in P4 registers can be used to save the hop count values for IP addresses by using hashed IP addresses as register indexes. This technique is described in [15].

3.1.5 History-Based IP filtering (HIF)

For this filtering technique a database of valid sources is maintained based on a history of normal traffic from those IP addresses. During the collection phase the number of packets that have been received from a source and the number of days a source has been seen are stored. During the attack phase thresholds are used on the number of packets, the number of days, or both, so that all packets that have a value in the database below the threshold, or do not exist are seen as attack traffic and are consequently dropped. To ensure that only currently active sources are kept in the database a sliding window is used. This means that IPs that have not been seen for a certain time are removed from the database. This technique fails if the attacker can first simulate normal traffic, and then attack from the same source. [17] For implementation in P4 registers can be used as hashtables to store the necessary data. The sliding window can be implemented by checking the last seen timestamp while updating a packet or applying the filter. This technique is described in [18].

3.1.6 Path identifier (Pi)

This filtering technique uses a path identifier that is saved in a packet to drop all packets that have the same path identifier as a detected malicious packet. A later developed path identifier filtering technique called StackPi improved this concept in terms of performance and the amount of routers that need to implement this technique to make it succeed. This amount was lowered from 50% to 20%. Drawbacks of this technique are that multiple routers (20% of the internet) have to work together to achieve a reasonable amount of DDoS protection. Another drawback is that since the identifier has a small size, there will be overlap in different paths. Thus, it increases the chance of false positives. [17] The P4 implementation could use match-action tables in which the key is the path identifier of a packet. If another device detects an attack packet with a specific path-identifier, this identifier can be stored in the match-action table, with the drop action attached. This technique is not suitable for implementation on a single device, since it needs several routers to mark packets. This technique is described in [22].

3.1.7 PacketScore

This filtering technique uses Bayes' theorem to calculate the probability that a packet is legitimate based on baseline values that are calculated based on statistical analysis of normal traffic. This technique is described in [16]. A drawback of this technique is that is uses a lot of storage to store the attributes for normal traffic. [17] The generation of the nominal profile occurs in different periods. These periods are combined into a final value based on the occurrence rates of different measured attribute values. These rates are calculated by dividing the number of packets with a certain attribute by the total amount of packets. To combine these values usually loop constructs are used to calculate a resulting value for each attribute. Since P4 has no loop constructs (see section 2.1.1) another way should be found to do this. One way to solve this problem would be to store the total amount of packets for each period. However, then for combining the results of multiple periods into one result, again loop constructs are necessary. To work around that the results of each period should be kept in memory until an attack happens. This is not feasible in practice due to memory constraints.

3.1.8 Confidence-Based filtering (CBF)

This filtering technique follows the same idea as PacketScore in that it uses a profile of normal traffic to calculate a threshold below which a packet should be dropped. However, it can handle larger attacks because scoring and discarding packets is not related to attack intensity. Another benefit is that the calculations for CBF are easier than those for PacketScore. [13] For the calculation of confidence values, the occurrences of attribute values are counted during a time-window. At the end of each time-window the confidence values are calculated based on those stored values. For the generation of the nominal profile the same implementation problems arise as with PacketScore. Implementation in P4 follows a similar approach to an implementation for PacketScore.

3.1.9 Signature-based filtering

In this filtering technique packets are compared against known signatures of DDoS attacks that have been created based on previous attacks. An example of signatures that could be used can be found in [2]. This technique can very accurately drop packets belonging to a DDoS attack if the signature is known. A drawback of this technique is that at least one attack has to succeed before it can be blocked, because the signature is not known in advance. Implementation in P4 using the signature structure of [2] should be possible since the match-action tables could be used to look up IP addresses, ports and protocols. There is a multitude of different Signature-based filtering techniques. Therefore there is not a clearly defined algorithm for implementation.

3.2 Filtering technique selection

3.2.1 Requirements

To evaluate the suitability for implementing a filtering technique in P4 one must be selected that will yield a useful result. Therefore this technique should be a popular technique, since that means that an implementation is useful for the general public. Another benefit of popular techniques is that the amount of documentation and examples that are available is bigger, which facilitates the implementation. Furthermore, for testing purposes it is convenient that the algorithm can be tested on a single device. To advance the state of the art it is necessary for this research to yield new results, therefore there should not already exist an implementation of the selected filtering technique and the implementation should not be trivial.

As a result of the above reasoning, the selected filtering technique should have the following characteristics.

- It must be commonly used in real-world applications
- It must be implementable on a single device
- It must not already have an open-source implementation in P4
- It must have potential for an implementation in P4 (i.e. it must not be known to be impossible beforehand)

3.2.2 Selection

Based on the survey of the filtering techniques listed above, there are several that meet the requirements set in section 3.2.1, they are listed below.

1. History-Based IP filtering (HIF)
2. Hop-count filtering (HCF)
3. Signature-Based filtering

For Signature-Based filtering there is no single algorithm to implement, therefore this technique is not suitable for this research because then too much time would go into choosing and designing a good Signature-Based filtering technique instead of focusing on the objective stated in section 1.1.

HIF and HCF both use previous normal traffic to set a standard which new packets must adhere to. However in HIF this matching is less strict than in HCF since HIF uses a threshold which packets must be above, while HCF uses an exact value. This makes HIF more flexible because with different thresholds the algorithm can be adapted to the kind of traffic that a server is receiving. Also, the different filtering criteria of HIF make it suitable for a step by step implementation in which each step can be tested independently.

Because of these reasons HIF is selected as the algorithm that we implement in P4.

4. IMPLEMENTATION

This section describes the P4 implementation of History-Based IP filtering (HIF), the algorithm selected in section 3.2. As described in section 3.1.5 the algorithm is divided into two phases, the training phase and the attack phase. The implementation of these phases is discussed below. Where necessary the algorithm is explained in more detail.

The implementation only filters IPv4 packets because the most suitable test data and DDoS data available only contains IPv4 addresses. Besides that, the only notable difference of using IPv6 for the implementation would be a deviation in the probability of hash collisions, due to fact that IPv6 has more addresses, which would not yield results about the suitability of P4 in the area of this research.

4.1 Data storage

The data that is needed for the filtering during the attack phase is the number of days that the IP has been seen and the number of packets that have been received. In addition, to implement the sliding window and to count the number of days a source IP has been seen, a timestamp of the previous packet is needed, therefore, this timestamp should also be stored.

So the fields that need to be stored per source IP are

- Number of packets
- Number of days
- Timestamp of previous packet

Match-action tables were considered as a storage method for this data because of the big amount of memory that is available to them. The action would then be the same for all entries, namely the filter action. The data would then be stored as action parameters. Despite those benefits, they were not used because of the performance limitations described in paragraph 2.1.1.1. A problem that was observed with an implementation using tables for storage was that the number of packets that were observed was significantly lower than the number that was sent. This is presumably due to the fact that the delay in connection between data plane and control plane caused the processing of packets to use outdated data.

The remaining option for the data storage was to use registers. They are used as hash tables, the IP address is hashed, and the resulting number is used as the index of the register. The main drawback of using registers is that there is a limited amount of memory available (see paragraph 2.1.1.1). The result of this is that the hashing algorithm (CRC32) has to be limited to a certain target space, the size of the register. The biggest register size that could be used as the hash map in the BMV2 switch was empirically determined to be 2^{22}. For higher values than that, the program would occasionally crash during initialisation. For hardware switches this boundary for the size of the registers is predefined and can usually be found in the device specification.

Due to the fact that the source space is bigger than the target space, there are collisions in the hashes, i.e. multiple source IPs will have the same hash. The consequence of this is that there are cases in which multiple sources that would not reach the thresholds independently, may reach them together because of a collision, or a source would pass during the filtering phase, because a colliding source has reached the thresholds. Another, more severe, problem is if attack sources have collisions with valid sources so that their packets are not filtered.

4.2 Training phase

During this phase, the data discussed in section 4.1 is collected. Saving the timestamp of each packet and counting the number of packets is trivial. However, in determining whether a source IP has been seen before in the current day some limitations were encountered. Normally, a loop would be used to repeatedly add the length of a day to the current start of the day until the difference between the current time and the start of the day is less than a day. Thus, a next day in which packets are received always starts an exact number of days after the previous day. Naturally, days in which no packets are received do not have to be considered. Since P4 has no loop constructs, this kind of algorithm is not possible, so there are two possibilities left. The first is to update the *day start* from the control plane by updating a register. However, this was not done in this implementation because, this requires the register to be updated every so often, which means that a scriptable API like P4 runtime [7] is needed. On the other hand, to change the switch from training to attack phase (as described in section 4.4) a register write is needed, which is not possible with P4 runtime (see section 2.2.1). The second possibility is to use an approximate calculation that does not include loops. In the implementation of this paper, the next day is always the arrival time of a packet, which means that if no packet arrives exactly one day after the previous day start, that previous day will be slightly longer. The impact of this algorithmic flaw is shown in section 6.2.

The HIF paper [18] states that only packets of valid TCP connections should be used to update the database. In this research that part of the implementation is omitted since the additional required data structures and language constructs do not differ from the ones used in the rest of the P4 implementation. However, such an implementation would require an additional register for saving a TCP status flag for each source IP, so the overall memory necessary will increase, which might present difficulties depending on the amount of memory available.

4.3 Attack phase

During this phase, packets are filtered based on the values that have been stored in the training phase. There are two rules based on which HIF can filter packets. The first is based on the number of packets that has been received from an IP, the packet threshold. The second is based on the number of days a source IP has been seen. In this paper both of these rules are used, after the example of [18].

4.4 Phase transitioning

The phase of the switch is toggled between training and attack phase using a one-bit register which is set using the BMV2 CLI interface. In a production implementation this would be set as a result of an external attack detection mechanism.

5. VERIFICATION

Table 2: Datasets of legitimate data with relevant test parameters: the number of algorithmic days and the replay speed

Name	Description	Alg. days	Replay speed
ftp-small	1 day of ftp data from [4]	50	400x
ftp-big	10 days of ftp data from [4]	10	200x

This section shows that the implementation of the algorithm is correct by analysing the processed output of the BMV2 switch and comparing it to expected values that are calculated by a Python program that performs the same action as the switch on the same data. Differences in the output are discussed.

5.1 Test data

The perfect dataset for testing an HIF implementation would be at least a week of data and a spoofed DDoS attack on the same server. This is because if the attack and the data are from the same server, the most realistic performance measurements are obtained. Otherwise, if the servers differ, there will most certainly be less overlap in the IP addresses than expected in a real scenario.

In the absence of such a dataset, the datasets that are described in table 2 are used. Some of the tests are executed on the smaller dataset because processing and analysing that data takes considerably less time than for the big dataset. For most of the tests the big dataset is used, because it is closer to a real-world situation, and will thus yield more accurate results.

In addition to these sets of legitimate data, also DDoS data is necessary. This is obtained from DDoSDB [2] by contacting its institutor.

Since for HIF only the source IPs are important, a custom dataset is generated with one packet per IP found in the DDoSDB data. The amount of packets per IP address does not matter for HIF because either all or none of the packets of an IP will be dropped.

For the tests, the datasets are split in two parts with a ratio of 9:1. The bigger part is used as training data for the training phase. The smaller part is mixed with the DDoS data and used as test data for the attack phase.

5.2 Setup

The testing setup is a mininet [5] setup in which two hosts are connected to each other via a BMV2 switch. The packets are sent from the first host to the switch, which forwards them to the second host. The speed of the replay depends on the average speed at which packets arrive. For the small dataset the packets did not arrive that fast after each other, so the replay speed could be higher than for the big dataset. Meanwhile, the input and output traffic of the switch is saved in pcap format to be analysed by the Python program later.

The results of this analysis are shown in fig. 2 and fig. 3. They show the result of the training phase, and the filtering results of P4 in relation to Python.

5.3 Results

5.3.1 Training

The results of the training phase are shown in fig. 2. It shows how the sources relate to the packet and days thresholds. In the figure two threshold combinations are shown, the initial, in which the days threshold is 5 and the final in which the days threshold is 1. Sources that lie in the upper right quadrant of the utilised threshold combination exceed both thresholds and packets from those sources will thus be admitted during an attack. Packets from all other quadrants are dropped. From fig. 2 it is clear that a significant portion of the addresses fall below the initial days threshold of 5. This naturally results in an unacceptable false positive rate. Because of this reason a days threshold of 1 is used, which effectively disables its function.

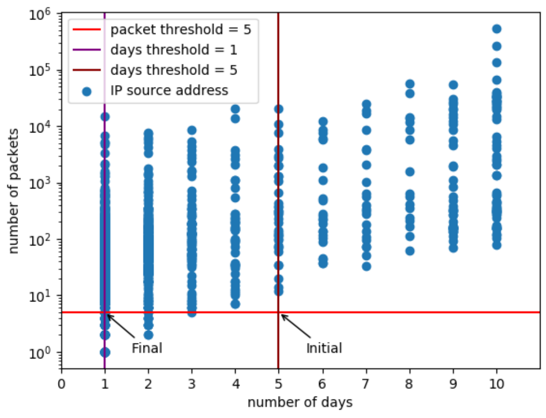

Figure 2: Result of the training phase on ftp-big, showing how sources related to the day and packet thresholds (see table 2)

5.3.2 Filtering

In fig. 3, the output after the filtering by P4 is shown. The input is not shown because the enormous amount of input traffic obscures the differences between Python and P4. The sources marked in red are DDoS sources that were passed by P4 because they had values in the database that were higher than the threshold, however, they were not seen before by the Python implementation (i.e. they had no value in the database that was constructed during training). The Python implementation did not pass any DDoS packets. There can be two reasons that the packets were seen by the switch and not by Python. The first reason is that they were not captured in the pcap files that were saved by mininet. During the tests on ftp-big (see table 2) a difference in the number of packets reported by P4 and by Python was observed. P4 reported 4655 (0.18%) more packets than Python. So there is a difference between the number of packets that went through the switch and the number of packets saved in the pcap files. However, it is unlikely that this is the cause of the difference in filtered output because the switch reports that from some of these differing IP addresses it has received over 8000 packets, which is far more than can be accounted for by the difference in the pcaps. The second, more likely reason it that this is the result of the hash collisions discussed in section 4.1. The IP addresses would, in the switch, have the same hash as an IP address that was seen, but in Python the hashes would be different. In table 3 it can be seen that the whole difference between P4 and Python is in the DDoS packets. So the way in which the filter passes legitimate traffic is exactly the same for both P4 and Python. The results of filtering for ftp-big (see table 2) are shown in table 3.

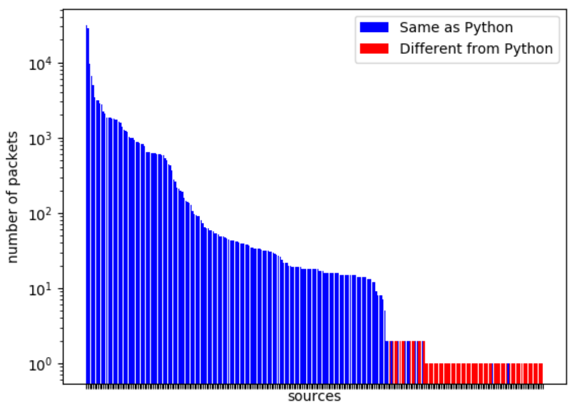

Figure 3: The filtered output of the switch for dataset ftp-big (see table 2).

Table 3: The filtering rates for P4 and Python for ftp-big (see table 2)

Rate	P4 (%)	Python (%)
True drop rate	99.87	100.00
False drop rate	10.19	10.19
False pass rate	0.13	0.00
True pass rate	89.81	89.81

6. DISCUSSION

This section discusses different design choices, in addition it analyses and discusses their influence on the results.

6.1 Parameters

This section discusses the selection of values for the different parameters of HIF.

6.1.1 Day

The length of an algorithmic day (i.e. how long a day is in the code) has to be defined. For the big dataset this can just be the actual length of a day divided by the replay speed multiplier. However, for the small dataset, it should be chosen sufficiently small so that multiple algorithm days happen within the one day of data. Therefore, the length of a is decided to be 20000 times as small as a normal day, so that at a replay speed 400 times the normal speed, 50 algorithmic days happen. This amount is enough to give sources a chance to appear on multiple days while keeping the days long enough to distinguish between regularly connecting clients and incidental connections.

6.1.2 Timeout

The timeout parameter defines the size of the sliding window, i.e. the time after which an entry in the database is deleted if no packet with the same source IP is found. According to the example of [18] the timeout was initially set to two weeks.

On ftp-small (see table 2). the sliding window had a negative impact on the performance, because due to the nature of ftp, clients typically send packets in bursts, in between which they do not send packets for some time. This behaviour would result in sources timing out even though they do have legitimate behaviour. Besides that, the sliding window is used to get a higher *true drop rate* and a lower *false pass rate*, which as we can see in table 3 is not possible for our dataset. For these reasons the sliding window was disabled.

6.1.3 Packet threshold

The packet threshold determines the number of packets that have to be received from a source IP for packets from that address to be passed.

The packet threshold was set to 5 according to the example in [18]. It has been compared to a threshold of 1 for ftp-big (see table 2). This resulted in very small differences in the rates (order of magnitude 0.01%).

6.2 Days calculation algorithm

Because the arrival time of the first packet after a day was used as the start of the next day, days are too long if a packet does not arrive at exactly the right time. The influence of this algorithmic flaw is analysed on ftp-small because it has more algorithmic days than ftp-big. The results in the number of days an IP has seen differs for 24 of the 622 IP addresses (3.85%). The differences are not higher than 3, while the highest number of days in the dataset is 27. The influence on the filtered output depends on the threshold for the number of days. When using the same method for calculating the next day there is no difference in the number of days.

In this research the days threshold is set to 1 (see section 5.3.1), therefore there is no influence of this flaw on the results.

7. CONCLUSION

As seen in section 3.1, out of the 9 techniques, 2 can definitely not be implemented in P4. Namely, *PacketScore* and *Confidence-Based filtering (CBF)*, this is due to the lack of loop constructs in P4. *Ingress/egress filtering* and *Martian address filtering and source address validation*, already have implementations in P4. The other techniques have varying degrees of potential. *Route-based packet filtering (RPF)* and *Path identifier (Pi)* can be implemented in P4 with relative ease because they require only matching on rules that can be independently stored in the match-action tables by the control plane. Whether *Signature-based filtering* can be implemented depends on the exact algorithm. If the algorithm matches signatures that can be stored independently by the control plane, as is the case for RPF and Pi, it can be implemented, however if data needs to be gathered from the processed packets and stored by the data plane, an implementation is cumbersome. *Hop-count filtering (HCF)* is quite similar to *History-Based IP filtering (HIF)* in implementation, it will therefore probably have the same limitations.

The case of HIF has been discussed in more detail. Through an implementation of this algorithm several limitations of P4 have been encountered and circumvented where possible. Firstly, the lack of loop constructs, can make it difficult to implement known algorithms correctly and can sometimes make an implementation completely impossible because data cannot be manipulated in the way that it should, as seen for CBF and *PacketScore*. Secondly, the fact that the big memory in match-action cannot be used by the data plane for storage. This makes that either the control plane has to be used for the action of storing data that is usually gathered in the data plane, or that other, smaller, storage mechanisms have to be used.

Which brings us to the last limitation, which concerns the registers. Registers, even though not as big as the match-action memory, can be used to store significant amounts of data, however, this may not be enough for a perfect implementation, as is seen in the case of HIF. Another drawback of registers is that only base types can be stored, and no user-defined structures. This may make some complex implementations more difficult or less able to efficiently use the available space.

To summarise this conclusion, P4 targets a use case where actions are performed based on match-action tables that are filled from the control plane. Because of this, using it for storing data from the data-plane has its limitations. However, by choosing the right algorithms and workarounds it is possible to achieve satisfactory results, as is seen in table 3.

8. FUTURE WORK

The probability of the hash collisions described in paragraph 2.1.1.1 is currently not known in full, it is unknown how much the probability of a collision for IPv6 differs from IPv4. In addition, research should be done on the spreading of the hashes over the possible hash values. There may be room for improvement regarding the current hash algorithm. Furthermore, some of the other filtering methods discussed in section 3.1 could be implemented to have a more complete evaluation of the suitability of P4 for implementing those techniques.

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