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Network traffic capture and analysis

Bachelor's thesis

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ZADANIE BAKALÁRSKEHO PROJEKTU

Meno študenta: **Belluš Tomáš**

Študijný odbor: Počítačové inžinierstvo

Študijný program: Internetové technológie

Názov projektu: **Zber a analýza dát o sieťovej premávke**

Zadanie:

Poznať rôzne parametre premávky uzlov v sieti môže mať význam z pohľadu administrácie, bezpečnosti alebo aj z teoretického hľadiska pri vypracovaní modelu, ktorý môže slúžiť na predikciu správania sa siete. Vypracovanie praktických nástrojov pre získavanie relevantných dát je základom pre ich ďalšie výhodnotenie.

Analyzuje možnosti získavania údajov o sieťovej premávke v rôznych vrstvách, v OS typu Unix, v reálnom čase. Navrhnite systém pre zber a uchovávanie týchto dát (ako napríklad čas, IP adresy, porty, veľkosti a pod.) pre zvolený systém. Ďalej spôsob ich analýzy, výhodnotenia a prezentácie, pričom systém by mal dať odpovede na otázky ako: v ktorých časoch sú využívané ktoré služby, v ktorých krajinách sa najčastejšie nachádzajú zdrojové a cieľové uzly komunikácie, aké objemy dát sa prenášajú, vytvoriť štatistický model dĺžky paketov, časové priebehy, trendy a predikcia uvedených charakteristik a pod. Systém implementujte a overte v reálnej premávke.

Práca musí obsahovať:

Anotáciu v slovenskom a anglickom jazyku

Analýzu problému

Opis riešenia

Zhodnotenie

Technickú dokumentáciu

Zoznam použitej literatúry

Elektronické médium obsahujúce vytvorený produkt spolu s dokumentáciou

Miesto vypracovania: Ústav počítačového inžinierstva a aplikovanej informatiky, FIIT STU, Bratislava

Vedúci projektu: Ing. Dušan Bernát, PhD.

Termín odovzdania práce v zimnom semestri 11. decembra 2018

Termín odovzdania práce v letnom semestri 07. mája 2019

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Hereby I declare that this bachelor's thesis was prepared as an original author's work under the supervision of Ing. Dušan Bernát, PhD.. All the relevant information sources, which were used during the preparation of this thesis, are properly cited and included in the bibliography.

in Bratislava,

signature

.....
Tomáš Belluš

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Chapter 1

Introduction

Ever since the first two network devices, whether in telecommunications or computer networking, exchanged data in some manner, we began to urge ourselves to send, receive and analyze data. Sending and receiving for communicating, and analyzing for understanding. Nowadays, these concepts are very actual in network security, network statistics and network devices such as routers, switches, firewalls, servers or any end-point devices. Applications require fast packet capture mechanisms for further processing, to keep up with the world's ever-increasing trend of transfer rates.

The Internet Protocol version 4 (IPv4) address range is, for a long time now, not enough for all devices connected to the largest network - the Internet. It implies that it is directly proportional to data being transferred over the Internet. This raises the need for applications, products or complex infrastructure solutions for keeping up with today's technologies.

With increasing network transfers, number of network devices, new frameworks and transfer protocols, improved algorithms and overall network security comes the threat of data theft, (distributed) denial of service attacks, compromised system or network and many other. Therefore, real time network traffic analysis is of utmost importance for national security authorities (mainly cybernetic security department), security or network companies and even end-point users. Network traffic analysis includes understanding and depicting various indications of either unlawful actions for security reasons or network transfers for statistical purposes. For both it means monitoring the correct functionality of network at hand.

Furthermore, each packet provides different decisive protocols that indicate information about the connection nodes and service used. A full understanding of the TCP/IP model and its layers is crucial for analyzing these services. Application, transport, network and link layer comprise the TCP/IP stack. Application layer is where applications exchange raw data, transport

layer connects sockets for data transfer, network layer forwards packets to destination and link layer checks credibility and handles the closest physical device connections over medium.

What are existing solutions to packet capturing mechanisms with network traffic analysis? How can we utilize existing packet capture mechanisms, reuse captured data analysis and identifying trends, threats and possibly predict future traffic? With packet capture and data analysis come storage systems, which need to be examined and evaluated. What known databases provide fast search process for real time network analysis and at the same time fast insertion rate, which would be sufficient for wire speed captures?

This thesis aims to answer and evaluate these questions. In addition, consider frameworks, systems and mechanisms explicitly for UNIX systems. Implement a system for packet capturing, store captured data to chosen database and finally analyze it with a framework or tools. Create visualizations of how the network behaves, depict trends, make predictions of given characteristics and analyze network packets on different TCP/IP layers.

[Chapter 2](#) analyzes packet capturing process, distinctions among various mechanisms in [performance](#) and techniques, [storage systems](#), [data for analysis](#) and [existing solutions](#). [Chapter 3](#) focuses on [system specifications](#), [system design](#) including the system architecture and [implementation](#) including a data model.

Chapter 2

Analysis

2.1 Packet capture mechanisms

The most critical part is real time data capture in network traffic, meaning capturing network packets using a framework or interpreted language library. It is a dependent process of hardware components like Network Interface Controller (NIC), processor performance and its properties (e.g. number of processor cores). Capture of every packet, which can be processed by arbitrary mechanism ordinarily takes place in the higher system layer - the user space. More efficient mechanisms have access to data, which fall under the jurisdiction of lower system layer - kernel space. Though, why is it more effective and efficient to access data in lower system layers? Kernel space is the operation system's (OS) core and an interface to hardware for the OS. More precisely, it is the access to shared kernel space, which altogether bypasses the additional copying and processing present with basic frameworks not utilizing efficient features.

Received data on NIC is stored in NIC buffers. NIC registers keep track of whether the buffers are full and ready for reading or sending. This indication is handled by interrupts from the NIC to the OS. OS copies the buffer content to kernel space buffers (called *m_buffs* or *sk_buff*¹). These buffers are not accessible by processes, but can be copied to user space or the process accessible memory. This is a typical scenario - two copies and interrupts needed for a process to access received data on the NIC. Possible improvements is to use, as mentioned above, buffers shared between kernel and user space, which eliminates one or more copies and interrupts from user to kernel space, leaving only one copy between NIC buffers and shared buffers. Other

¹These kernel buffers are expensive to create and vary in size. They are complex and include large amount of metadata. [20]

possibility is to have a NIC supporting multiple buffers, which split the load and each buffer is handled by different core simultaneously [19].

A problem arises with the ability to capture all traffic on wire with no increasing delay resulting in packet loss due to lack of buffer space. Solution may be a zero-copy mechanism which utilizes a NIC dependent direct NIC access (DNA) or a one-copy mechanism, which utilizes the shared buffers. This section analyzes packet capture mechanisms, with various efficiency improvements at high packet rates in network traffic.

2.1.1 Scapy and RSS

*Scapy*² for Python running on Linux systems operates in user space with no access to shared memory. At its core it utilizes Libpcap library and it is mainly a packet crafting library, packet decoder and a network sniffing mechanism on given interface [4]. In addition, it features filtering, detecting request responses and supports multiple existing protocols from all layers [10]. Even though, it has complex packet parsing, which makes it simple to extract any field, it is a huge bottleneck. It is present due to known Python complexity in lower layers of its implementation. While using scapy is a fast solution from development point of view, the execution time is crucial here, therefore its packet capturing performance is insufficient (see [section 2.2](#)).

Additional resolution to the bottleneck, despite not using scapy, may be applying improvements to data processing on NIC driver level. It would require enabling CPU to process incoming packets by dividing received data among multiple CPU cores. On Linux platforms it is referred to as *Receive-Side Scaling (RSS)* and it "distributes network receive processing across several hardware-based receive queues" [17]. More precisely, each queue will be handled by single core independently and simultaneously. Unfortunately, this feature is dependent of the NIC driver.

2.1.2 Packet socket

Creating a file descriptor *packet socket*³ provides receiving and sending packets at datalink layer. It means that packets are captured before any processing in the Linux network stack as raw frames including all protocol headers [2]. A packet socket with raw network protocol access (raw socket) is opened by a system call (see [Listing 2.1](#)), where the first argument must be

²<https://scapy.net/>

³<http://man7.org/linux/man-pages/man7/packet.7.html>

*AF_PACKET*⁴ [3], which indicates the protocol family. *SOCK_RAW* parameter identifies that it is a raw socket providing a whole encapsulated Ethernet frame. Macro parameter *ETH_P_ALL* specifies the socket protocol, which is expected on receive so in this case we require all protocols to be passed to socket interface [2].

```
1 int fd = socket(AF_PACKET, SOCK_RAW, htons(ETH_P_ALL));
```

Listing 2.1: Raw socket system call

All in all, the packet socket is the interface receiving raw frames, or packets in case of trimming out link layer header, directly from the NIC and efficiently bypassing the network stack processing. This is an advantage concerning performance, because it produces only one copy of received data (from NIC driver to packet socket file descriptor) [28] [27]. The shared memory between kernel and user space is the packet socket file descriptor. In contrast with basic address family *AF_INET*, packet socket provides socket option for packet capture statistics (PACKET_STATISTICS), which is crucial for performance testing. In comparison with scapy it is the opposite in development and execution time point of view - it is presumably faster than scapy, but more complex to implement.

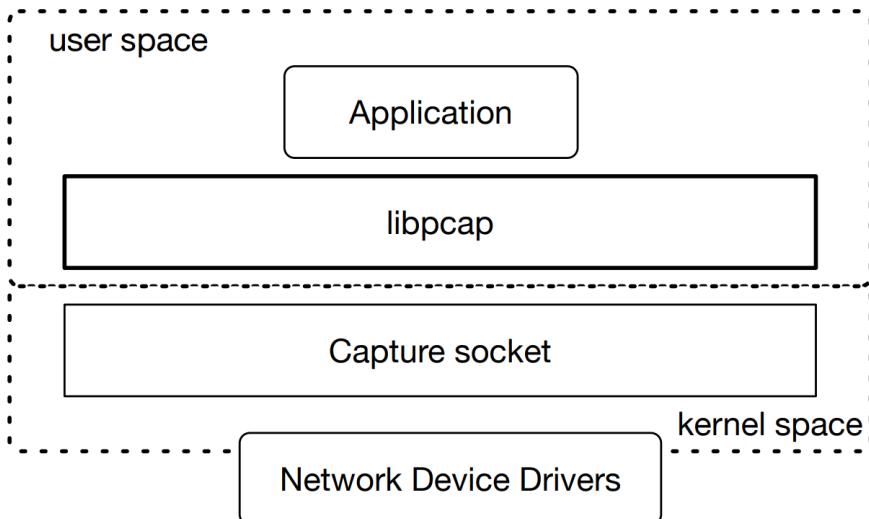


Figure 2.1: UNIX packet capture architecture for Libpcap or packet socket

⁴AF_PACKET is interchangeable with PF_PACKET and they stand for Address Family and Protocol Family respectively specified the communication domain. [3]

2.1.3 Libpcap

*Libpcap*⁵ is an user space library designed mainly for capturing Ethernet frames. It is a cross platform library for UNIX systems not only for C/C++ programming (e.g *tcpdump*⁶ and *wireshark*⁷), but for other more abstract languages (Python, C#, Java, etc.) it exists in form of wrappers [9]. An user space library does not utilize kernel network stack, rather it reads raw Ethernet frames from opened socket queue in kernel space. Therefore, frame decapsulation is handled by libpcap and any protocol data, of parsed frame at hand, is accessed by libpcap's Application Programming Interface (API) (see Figure 2.1). Libpcap uses PF_PACKET [21] [8] since version 0.6 release (year 2001) with kernel 2.2 support and later [23].

Moreover, as of libpcap release 0.9.5, this library supports capture statistics for protocol family PF_PACKET by a *getsockopt()* system call [24]. In reference to *scapy* and *packet socket*, libpcap provides more abstraction to implementations by wrapping socket operations to library functions and similar performance to packet socket.

2.1.4 PF_RING

Moving from user space library to the kernel space modules and possible zero-copy mechanisms, brings *PF_RING*⁸. On socket layer it is a protocol family, replacing PF_PACKET, but it requires loading a kernel module. On application layer, PF_RING has an API for accessing received packets. PF_RING lacking extra enhancements and independent of NIC driver is referred to as PF_RING Vanilla. As of performance, through Linux New API (NAPI)⁹ the kernel module copies polled packets from the NIC to shared memory ring buffers accessible by user application (see Figure 2.2) [15]. This process bypasses Linux network stack and the standard NIC driver. On the other hand, the performance depends on multiple hardware-based queues (RSS) in form of shared memory ring buffers (see Listing 2.2). Nevertheless, at least one shared memory ring buffer is created after loading the module to kernel. [16]

```
insmod driver_module.ko RSS=4,4
```

⁵<http://www.tcpdump.org/manpages/pcap.3pcap.html>

⁶<http://www.tcpdump.org/manpages/tcpdump.1.html>

⁷<https://www.wireshark.org/>

⁸https://www.ntop.org/products/packet-capture/pf_ring/

⁹NAPI is a performance increase for packet capturing at higher packet rates, by enabling packet polling, therefore decreasing number of interrupts which otherwise would overwhelm the CPU [5]

```
# enables 4 queues per interface (in this case two)
# the driver_module is the PF_RING enabled NIC driver
```

Listing 2.2: Enabling RSS [14]

Worth mentioning is the PF_RING_ZC, which is a zero-copy alternative to PF_RING Vanilla. It is strictly NIC driver dependent framework, which neglects NAPI, kernel modules and standard NIC driver to maximize efficiency by directly accessing NIC (DNA) (see Figure 2.2). Inserting the correct PF_RING-provided NIC driver enables an interface to be opened in zero-copy mode¹⁰. Any application can access packets through its API on 1-10 Gbit links at wire speed [12], if the kernel is bypassed. Otherwise the driver replaces the standard NIC driver and is faster compared to PF_RING Vanilla [13]. Disadvantages are, that while accessing NIC in zero-copy mode, standard networking is on hold until the device at hand is closed [13] and due to bypassing kernel packet filtering is missing [12].

Most valuable is the modified libpcap library¹¹ (pfring-libpcap) provided by the PF_RING framework. Pfring-libpcap requires the PF_RING module inserted and applications need to be recompiled with linking the new libpcap and specifically linking PF_RING library (libpfring) [11].

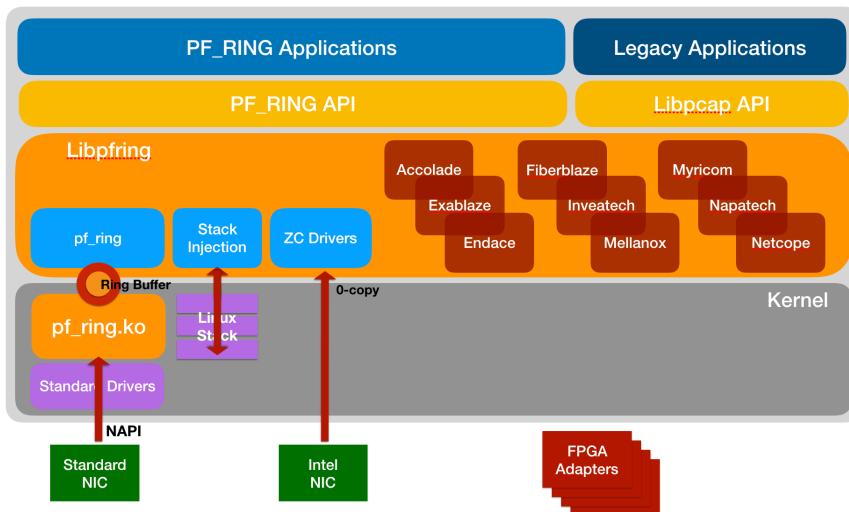


Figure 2.2: PF_RING variants and architecture overview

¹⁰Interface in the zero-copy mode has the "zc:" prefix (e.g. eth0 in zero-copy mode is accessed by zc:eth0). [12]

¹¹https://github.com/ntop/PF_RING/tree/dev/userland/libpcap-1.8.1

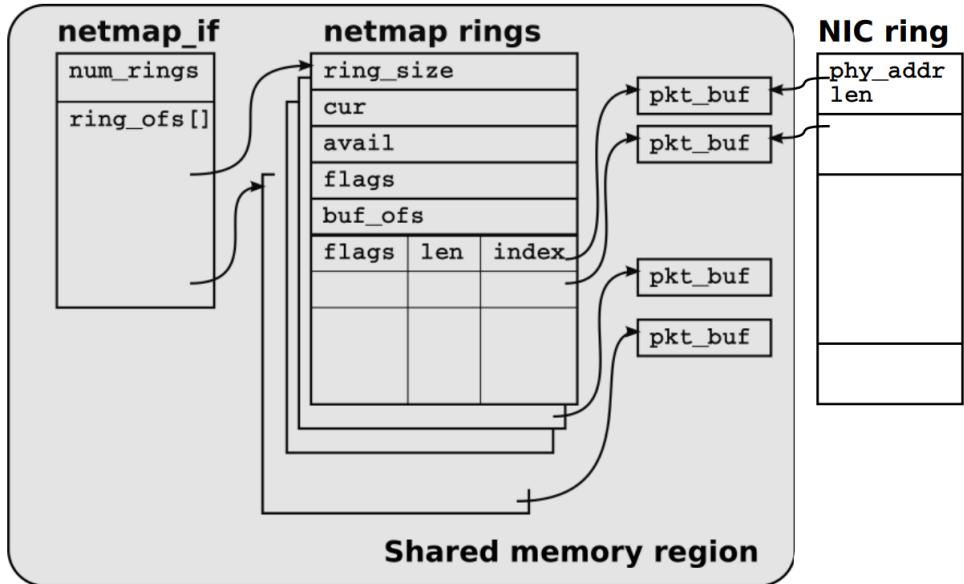


Figure 2.3: Netmap ring buffer design

2.1.5 Netmap

Last, but not least capture mechanism with an API is *netmap*¹². The current paragraph is derived from a report on Luigi Rizzo's netmap [19]. "It is a framework to reduce the cost of moving traffic between hardware and the host stack" [19]. Netmap targets the processing bottleneck by utilizing, similarly as PF_RING or packet socket, the shared memory consisting of netmap packet buffers and netmap rings (buffer descriptors). The netmap packet buffers are shared between NIC rings and netmap rings, meaning that application processes access the packets in cost of one copy. In addition, the buffers are circular (ring buffers) and are designed (see Figure 2.3) to eliminate most of the processing time. Standard NIC uses ring buffers for received data and the implementation of netmap rings is a replica of those buffers. The *netmap_if* is a descriptor table of netmap rings mainly used when multiple netmap rings are used for load balancing. In contrast with standard Linux packet capturing (I/O operations) process, where the buffers holding packets (*sk_buffs* or *m_buffs*) are allocated and deallocated throughout the capturing process, the netmap framework preallocates *pkt_bufs* (see Figure 2.3) to bypass this time consuming operation.

Moreover, it requires a modified driver to be loaded to kernel, which provides maximum performance at wire rate if the netmap native API is used.

¹²<http://info.iet.unipi.it/~luigi/netmap/>

Just as PF_RING, netmap provides a netmap-based libpcap by creating a modified library, which maps libpcap standard calls to netmap calls [19]. Even though, the netmap libpcap has weaker performance in comparison with its native API, it does show improvement to the libpcap library [20]. For compatibility purposes, opposing to the native API the netmap libpcap may be the most efficient mechanism variant.

2.2 Performance testing

All of the above are potentially effective packet capture mechanisms, but only few are efficient enough to produce expected results in reasonable time. Performance testing of any mechanism means to simulate expected network traffic environment and mark down elapsed time or other performance output based on specific mechanism. Requirements for efficient capturing mechanism are minimal or no packet drop rate combined with wire rate capture, bypassing kernel processing and minimizing data copies. Packet drop rate is the ratio of dropped packets and total packets received by a NIC during a given period of time. At wire rate capture, packets are received with no delay. Bypassing kernel altogether (except for handling interrupts) and minimizing data copies results in performance increase and it is a crucial mechanism feature. These are the three aspects for testing and comparing all [mechanisms](#) analyzed.

This section focuses on performance testing process and its results. Packet capture efficiency (drop rate) of received traffic and time elapsed are measured and evaluated. Brief focus on [testing automation](#), followed by the [specific tests](#) of both mentioned aspects and finally providing test [results](#).

2.2.1 Automation

A bash script is used for efficient performance testing (see Appendices A and B) of both packet capture efficiency and elapsed time of captured traffic. For most mechanisms the implementation is straightforward, but running multiple executables (binary files) of single C program with various libpcap versions requires additional variables. It was the most crucial part of testing, since only one libpcap library version can be installed on a system. Appending the `/etc/ld.so.conf` with directory paths of other libpcap versions partially solved the problem. Although, only one extra libpcap version can be added this way, since the linker works in a "first match" sense. For example, the target library was pfring-libpcap, but it was linked to netmap libpcap (see [Listing 2.3](#)).

```
# paths to multiple libpcap libraries
/home/tomas/libpcaps/netmap-libpcap/
/home/tomas/libpcaps/PF_RING/userland/libpcap-1.8.1/
```

Listing 2.3: Contents of /etc/ld.so.conf.d/libpcaps.conf

Solution is to link the library directly with the program source file, and on execution prefix the binary with overriding the LD_LIBRARY_PATH [1] environment variable (see Appendix C). This variable may contain library paths to be searched before the library configuration file is used (*/etc/ld.so.conf*). Setting the variable in line with execution makes it temporary, rather than sourcing it every other execution for different libpcap version. Using the *ldd* command, which prints the shared object dependencies, validates this method a success.

2.2.2 Tests

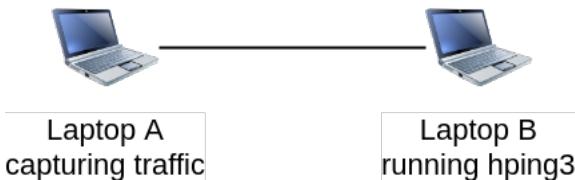


Figure 2.4: Diagram of testing scenario

Machine	CPU	RAM	NIC	OS
Laptop A	Intel i5-7300HQ, 2.50GHz x4	16 GB	Realtek 1Gb	Ubuntu 18 64bit
Laptop B	Intel i5-2430M, 2.40Ghz x2	6 GB	Realtek 1Gb	Kali Linux 64bit

Table 2.1: Computer hardware specifications

Testing the packet capture efficiency required a traffic generator to simulate a high frequency of packets. For this purpose, Kali Linux has a generator tool *hping3*, which is capable of sending 179 000 packets per second (179 Kpps) on a Realtek¹³ adapter. Even though, it is not a perfect real life traffic simulator it is sufficient enough to depict differences between some mechanisms. The testing environment consisted of two computers as shown

¹³RTL8111/8168/8411 PCI Express Gigabit Ethernet Controller

in [Figure 2.4](#) with specifications in [Table 2.1](#). Drop rate is the best indicator of an efficient capture mechanism. Each test was constructed by the *hping3* command generating raw IP packets with 120-byte payload at different frequencies (see [Appendix D](#)). Each mechanism was implemented as a simple C program or Python script and tested 5 times in 30 second time blocks. Refer to the Appendices for [bash script](#) for testing packet capture efficiency.

In contrast, testing capture elapsed time proves the wire speed capture of a mechanism. Similarly, *hping3* tool was used for generating traffic at maximum rate (179 Kpps) using flood mode (see [Appendix D](#)). Each mechanism was tested 5 times with various number of packets to be captured subsequently returning elapsed time. Refer to the Appendices for [bash script](#) testing elapsed time.

In addition to this specific performance testing, a more precise and valuable tests were performed as part of the IIT.SRC 2019 conference included in [Appendix G](#).

2.2.3 Results

Graphs displaying results of the performance tests are included in the Appendices [E](#), [F](#) and [G](#).

Packet capture efficiency

Results have proven that *scapy* is not effective at higher packet rates (see [Figure E.1](#)), which is due to the Python complexity. It makes the drop rate increase rapidly, until more packets are dropped than captured (see [Table 2.2](#)). Therefore, *scapy* is insufficient for capturing real time network traffic.

Elapsed time test			
Packet rate [pkt-s/s]	received	captured	dropped
20	600	591	9
194	5 820	5 726	94
2 010	60 300	59 413	887
20 050	601 500	87 711	513 789
179 000	5 370 000	88 012	5 281 988

Table 2.2: Scapy measured drop rate

Moreover, other mechanisms were efficient and captured all the traffic (no packets were dropped due to lack of buffer space). Referring to [Figure E.2](#),

packet socket is significantly faster at capturing packets at small rates, because it captures packets in a flow (one by one), rather than in batches¹⁴. As the rate increases, all mechanisms have zero drop rate and captured all packets. Deciding for a mechanism accords for potential zero-copy feature (netmap and PF_RING), since all are equally efficient. Even though, netmap and PF_RING could be compared as equally efficient, there are some major aspects analyzed in their respective sections, which breaks the tie.

With respect to this test, netmap is the most suitable choice, because it provides minimum copies of data received, it has no measured drop rates and it is utilized in a modified netmap-based libpcap library, which makes the program compatible with other libpcap versions.

Capture elapsed time

Measuring the elapsed time of set of operations comprises of marking the time before and after the execution of target commands. This would be reliable if the system's time would not change due to Network Time Protocol (NTP) bad update or other unpredictable changes. Alternative is the monotonic clock, which goes forward independently of system's time. For Python scripts monotonic clock is included in *time* module and for C it is included in *time* library by *clock_gettime()*¹⁵ system call.

As it was for testing packet capture efficiency, elapsed time of packet capture with scapy was radically slow. As a result, scapy was not tested for the maximum of million packets because of the predicted exponential increase (see [Figure F.1](#)). In comparison scapy was processing more than 30 seconds, while other mechanisms processed the same load in 500 ms. All other mechanisms captured packets in wire speed. [Figure F.3](#) compares average elapsed time for all considered mechanisms and netmap has processed million packets the shortest time. Even though, the bar graph shows differences between packet socket, netmap, PF_RING and libpcap, their performance could be the same due to inconsistent packet rate on wire. Nevertheless, netmap did not fail this performance test, so it remains as the most efficient choice.

2.2.4 Summary

There are multiple mechanisms considered and analyzed, but finally only netmap remained as the most efficient choice for both implementation and

¹⁴Capturing packets in batches means to copy or access multiple packets within one interrupt or read.

¹⁵https://linux.die.net/man/3/clock_gettime

performance reasons. Therefore, netmap-based libpcap could be utilized for this thesis for compatibility and performance reasons.

2.3 Data storage

Initially, as it may seem, the most critical part is real time packet capture. Although, the real bottleneck in whole data processing is data storing in real time with acceptable time delay. Storing captured data includes parsing raw data and send them to a remote database server for further data analysis. This section analyzes considered database systems and options.

2.3.1 SQL versus NoSQL

Using a Structured Query Language (SQL) database requires knowing the data model of the expected data - Relational Database Management System (RDBMS). This would require a complex data model of all possible fields of network protocols. SQL database stores full entries of data despite multiple empty fields, which produces extra disk space usage.

However, Non-relational Structured Query Language (NoSQL) database provides high flexibility with its data and a faster search. Data can be stored in JSON format, which makes it directly compatible with numerous parsers and any data manipulation. NoSQL databases are also characterized as key-value pair database systems, such as Redis database, which is a simple caching database, MongoDB or Elasticsearch.

2.3.2 ELK stack

ELK stack¹⁶ stands for *Elasticsearch*, *Logstash* and *Kibana*, but at this point there are more possible components of the ELK stack (e.g. *Filebeat*). The database component Elasticsearch, is a NoSQL database with no fixed data model. In comparison with a SQL database, where data is stored in records and tables, Elasticsearch stores data in documents and indices. Communication with an Elasticseach database is through various APIs using well known HTTP methods GET, POST, PUT and DELETE is in JSON query format.

An Elasticsearch index is populated by documents in JSON format and is defined by its settings API and mapping API. Via settings, the default

¹⁶<https://www.elastic.co/elk-stack>

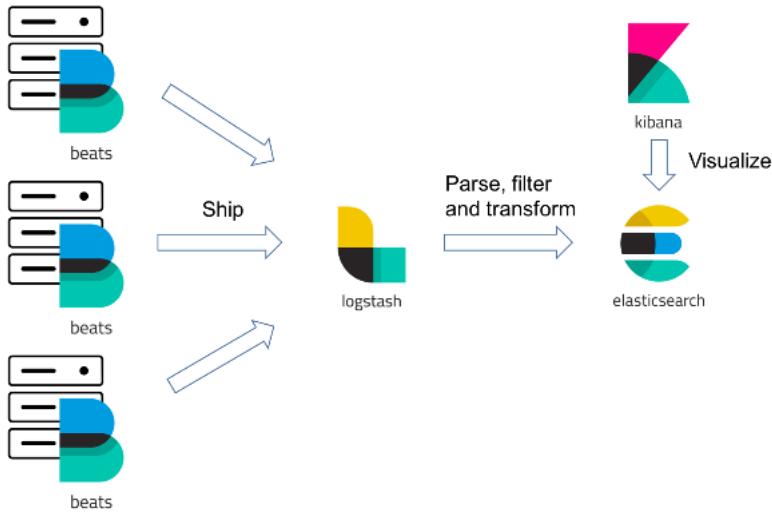


Figure 2.5: ELK stack set up including Filebeat

number of shards¹⁷ and the number of replicas¹⁸ [6] is defined. The mapping defines the document expected field's value type, but in case of lacking a concrete field mapping a document insertion does not fail.

Logstash provides parsing, filtering and queuing data streams from multiple sources to be inserted into Elasticsearch database (see Figure 2.5). It is useful for data enrichment and modification before it is inserted in bulk¹⁹ requests, rather than single documents. In its configuration are data input streams' specifications, filter clauses including transformations and output stream, which is usually the Elasticsearch database. It reads various input streams like Filebeat, Elasticsearch or raw TCP data stream.

In contrast, Filebeat is a lightweight component reading raw inputs, such as system log files or TCP raw data stream, which are redirected either directly to Elasticsearch or Logstash for more transformations and queuing purposes.

Kibana is an optional component of the ELK stack capable of visualizing and monitoring data in Elasticsearch (see Figure 2.5). It is an user friendly Elasticsearch interface, which abstracts the request queries when creating a visualization. For example, Kibana could serve as the Graphical User Interface (GUI) of the data stored in database for a network monitoring team

¹⁷Indices may be split into multiple sub-indices called shards.

¹⁸Shard copies, functioning as a failover. The number of replicas represents the number of copies of each shard.

¹⁹Documents wrapped in batches sent via one HTTP request [7].

of specialists. In addition, it recognizes a compatible timestamp formatted field for complex time period selections from any index or a specific data set. Moreover, to extend a field value, or creating a new field (visible only for Kibana) is possible by using scripted fields feature. All these features, creating visualizations or querying data in a NoSQL fashion are all advantages of using Kibana. Similarly as other ELK stack components, Kibana has a configuration file for specifying the Elasticsearch database.

In comparison with a SQL database, Elasticsearch documents are populated with only provided fields, despite being defined in the mapping or not. Whereas, SQL database does always insert into all fields even if they are empty. This Elasticsearch advantage saves space and makes the search elastic and fast. Utilizing ELK stack would require an external system connected to the sensor, or it could be residing on the same physical machine.

2.3.3 Redis

As an in-memory solution, where data analysis would take place as a part of the program and not as an external system connected to it, *Redis*²⁰ could be the solution. Redis is widely used as a caching database [18], which would require analyzing and implementing the visualization of data as a part of the final program. In addition, the data received would not be stored, rather cached in Redis database.

2.3.4 Sumamry

Since SQL databases are not suitable and Kibana provides the visualization tool for received data at arbitrary time period from the past, the ELK stack could be the right database system for this thesis.

2.4 Data visualization

Data visualization will be done by the ELK stack component Kibana. It meets all visualization requirements, such as selecting a specific time period, creating bar graphs, heat maps or trend lines and updating all as new data is received. This section discusses the data worth visualizing for further analysis. We will consider all layers of the TCP/IP model - [Network layer](#), [Transport layer](#) and [Application layer](#).

²⁰<https://redis.io/>

2.4.1 Network layer

Collected data at this layer include endpoint nodes, source and destination IP address, nested protocol of the higher layer, the size of the packet at hand and the Time To Live (TTL) field. IP address is a valuable field, containing multiple properties of the endpoint. The IP address provides the location of the node, Autonomous System Number (ASN) of a specific Internet service provider, whether its an unicast, multicast or broadcast or it being a private or public IP address (regarding IPv4). Moreover, the Total length field (16-bit packet length) indicator can be used to detect large data transmissions. If the length is and very frequent, it could indicate unlawful activity or predict link failure for it would not withstand that high packet rate.

OS	TTL	Packet Size	DF Flag	SackOK Option	NOP Flag Option	Timestamp Option
MAC OS X	64	60	1	0	1	1
Linux	64	60	1	1	1	1
Windows	128	48	1	1	1	0
Cisco IOS	255	44	0	0	0	0

Figure 2.6: OS fingerprinting with known IPv4 fields

Additionally, according to an article on operating system (OS) fingerprinting with packets [22], the TTL, packet size, flags and other option fields in the IPv4 protocol header can be used to determine the OS of the source endpoint (see Figure 2.6). Based on this assumption, the network traffic is analyzed from more security concerned point of view, by grouping hosts by OS. Other frequent network layer protocol Internet Control Message Protocol (ICMP), as the name defines, is used in various network use-cases for notification purposes. For example, *traceroute* protocol utilizes a property of a network device responding with an *ICMP Time Exceeded* message, when the TTL counter reaches zero. ICMP is also used in routing protocols, such as RIPv2, and is most recognized as protocol utilized by *ping* program used for debugging connectivity issues.

2.4.2 Transport layer

Transport layer provides more information on the communication, specifically port numbers, which identify the the service over which data is transmitted. Most recognizable Transport layer protocols are Transmission Control Protocol ([TCP](#)) and User Datagram Protocol ([UDP](#)). TCP is used for services requiring reliable transmissions and do not require fast delivery, whereas UDP provides fast transmit rates at cost not being reliable.

TCP

Services like SSH, FTP, Telnet, HTTP(S), BGP, SMTP and more are transferred by the TCP protocol. TCP header includes the source and destination port numbers, where usually one is higher (client public port 49152 - 65535) and the other is lower (server designated port 0 - 1023). According to this, it is possible to monitor when a well known service is being used in the network or when two endpoints are communicating with public ports. There are various indicators considering port numbers and the client-server model.

Furthermore, the TCP flags may be used to detect if a session has opened or closed with the SYN and FIN flags respectively. When following the standardized three-way handshake, the SYN flag stands for synchronize and should indicate a session start. The FIN referring to final, finish or finalize indicates the session close. This is only a brief explanation and of course there are more TCP flagged packets to be sent in between.

UDP

UDP is much simpler protocol with minimum header fields. It is the source and destination port numbers, length of corresponding UDP header with data and an optional checksum field. UDP is used by DNS, DHCP, TFTP, NTP and more services, which in comparison with TCP, provide fast file transfer service (e.g. TFTP) or generic service transparent for basic user (e.g. DNS, DHCP or NTP). Like all services, these have specific port numbers too, which can be read from packet capture even if the communication is encrypted²¹. The UDP datagram length can be used for UDP datagram size histograms and statistics or detecting a high data transmission on the network.

2.4.3 Application layer

Since most of network traffic on this layer is encrypted (e.g. SSH, HTTPS, etc.), there are minimum unencrypted protocols, which data could be analyzed or visualized. Unencrypted services include HTTP, Telnet over port 23, DNS, DHCP, FTP, TFTP and more. Raw data of these protocols could be used for deeper analysis.

²¹Communication is encrypted on the application layer.

Unencrypted and encrypted

In scope of this thesis, DNS packets may be the most valuable UDP-related application service for analysis. Detecting and monitoring a DNS communication has high security reasons. A possible amplification attack is realized by DNS packets.

Furthermore, HTTP, FTP and TFTP are unencrypted data transmitting protocols, which could carry potentially valuable informations. For example HTTP protocol could be used as the insecure communication between client and web server, database or any API. Intercepting this traffic could provide statistics of successful or failed requests ergo connections. File transfers over TFTP or FTP discloses all data, which is part of the transmitted message. For statistical reasons, it is not beneficial to capture this data, but detecting these protocols indicates usage of insecure transmission.

Others protocols (e.g. SSH and Telnet) are communication protocols acquiring connection with a host device for remote control. SSH is a secure communication protocol, which could be analyzed even when encrypted [25], but it is complicated. Nevertheless, the SSH communication is analyzed by detecting TCP protocol with source or destination port 22. In contrast, Telnet may be used for the same purposes as SSH, but it is not advised for it is an unencrypted communication channel. All sensitive data, such as user names, passwords or file system contents must be transmitted over to remote control terminal and thereby disclosing it all on the way.

2.5 Existing solutions

Existing software solutions [Moloch](#), [Wireshark](#) and [SolarWinds](#) partially depict the problem at hand.

2.5.1 Wireshark

*Wireshark*²² is a tool using standard libpcap library used for live deep packet analysis, pcap file analysis and following connection streams. It includes protocol hierarchy statistics, I/O graph view of received packets per second, endpoint and network session statistics and complex filtering options. Wireshark understands multiple protocols, outputs live packet capture and parses packets in hierarchical manner. Wireshark does not provide the required data visualizations.

²²<https://www.wireshark.org/>

2.5.2 Moloch

*Moloch*²³ is similar to wireshark in a way of reading pcap files and live network traffic. It utilizes Elasticsearch cluster for fast search operations and captures data with PF_RING module. Moloch provides network sessions statistics, unique value occurrence in sessions (SPI view or graph), network connections graph view of search results and Elasticsearch cluster and Moloch capture node statistics. Although, various visualizations of received data is not included.

2.5.3 SolarWinds

Specifically *SolarWinds Deep Packet Inspection and Analysis tool*²⁴, processes each received packet, but summarizes the gathered information to protocol statistics and packet classifications. Includes network latency testing in network segment for troubleshooting purposes. Does not provide deeper packet analysis (e.g. various protocol header fields) or arbitrary visualizations of captured data.

²³<https://molo.ch/>

²⁴<https://bit.ly/2FUWBRn>

Chapter 3

Problem solution

The solution to the analyzed components and merging it to one functioning system is described in the following chapter. The system specification, including its properties and use cases is outlined in [section 3.1](#). The design of the solution and the overall system architecture is introduced in [section 3.2](#). The concrete implementation techniques and class model is described in [chapter 4](#).

3.1 System specification

The final system must include the network sensor implanted in network for capturing packets and the ELK stack, which as the sensor is on a Linux machine. The sensor must then process and parse the received packets into a compatible JSON format for storing it to the database system via an API call.

The key processes that need to be included are as follows. Choosing an interface as the source of received traffic and specifying the direction (outgoing, incoming or promiscuous mode), specifying the database destination with an IP address and a port and provide filters to be applied on received packets. Furthermore, it must notify the user with potential errors or successful tasks (such as initialization of the sensor) in standard log files in designated system directory. The packet capture and further processing must not create a bottleneck and be ideally processing at wire speed. The system must have control over used space in the database. In such cases, the system finalizes the received data with summarized data and clear the disk space.

Considering the data visualization, various line graphs, bar graphs, heat maps and trend lines will be periodically updated as new data is received. These visualizations must be modifiable and it must be possible to create new

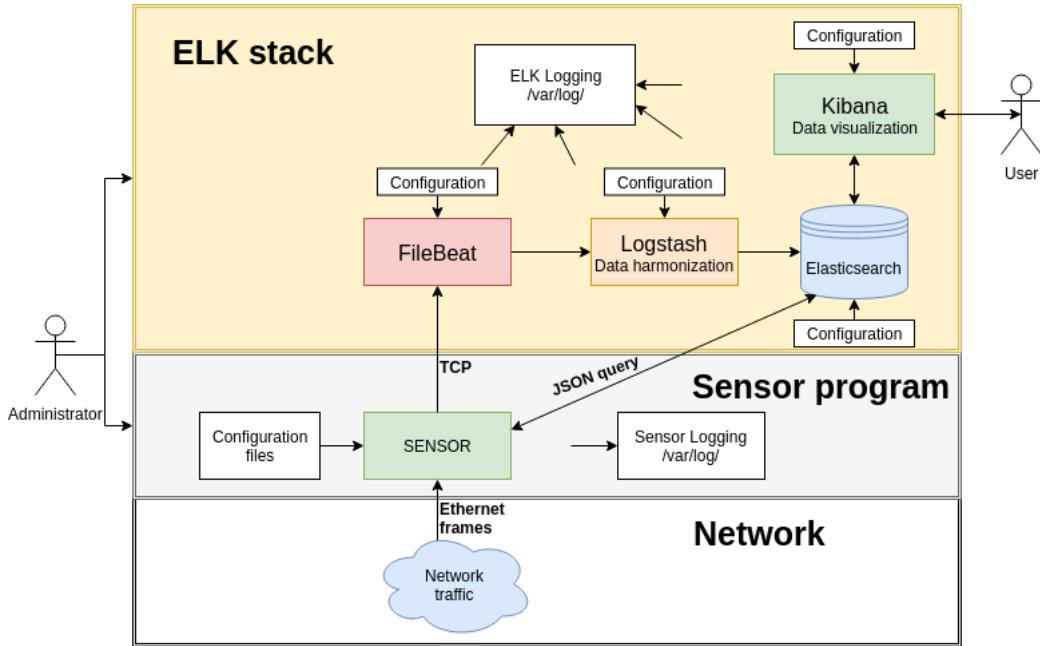


Figure 3.1: System architecture model

visualizations. The final data set must include all desired protocol header fields and packet meta data such as, timestamp of the received packet, source host of the received data and source interface of that host. The database system should not delay the data stream. The following visualizations must be possible to setup:

- What services in use at arbitrary time range.
- Show activity for a specific service at arbitrary time range.
- Network sessions' ($host_1 \leftrightarrow host_2$) activity.
- What is the geographical location of network communication nodes.
- Packet rate or bytes transmitted per arbitrary time unit.
- Statistical packet length models or histograms.
- Trend lines for predicting future traffic.

3.2 Design

3.2.1 Sensor

The sensor will run on top of netmap-based libpcap (supported by [test results](#)) and the chosen visualization tool and storage system is the ELK stack. Capturing packets on specified interface is part of the library. A suitable JSON library will be used for parsing the packets to JSON structures, which are send to the ELK stack for storage and visualization (see [Figure 3.1](#)). In between Kibana and the sensor, Filebeat will accept TCP data flow on an open port and forward it to Logstash service. Then Logstash will add harmonization data, remove unwanted fields and store data via the Elasticsearch bulk API.

3.2.2 Data processing and storing

The sensor will be designed as a Linux program utilizing a configuration file, configured by the user. Both interface specification and filters will be included in these configuration file. Configuration file validation will report to log files success or error. Similarly, the capture will be logged on initialization and log error occurrence. For parsing packet structures, the most suitable library regarding conformance, parsing time, parsing memory and stringify time is *RapidJSON*¹ [26].

Before any packet capture, an Elasticsearch index will be created with a given mapping in JSON format. Keeping consistent protocol field types, such as integers, strings or IP addresses is crucial to bypass Elasticsearch field recognition. Filebeat will accept TCP data flow on an open port and forward it to the Logstash service. Filebeat additionally appends some requested meta data, such as source host of the data and timestamp. Logstash has full control over this data and it will remove some extra meta data and add arbitrary static fields like overall data type identification (e.g. "sensor-data").

The sensor will periodically monitor the database disk usage, until it detects low free space. In such case, the data will be summarized by multiple query requests and a new identical index will be created. Similarly, it will monitor the sensor log files and periodically archive large log files.

¹<http://rapidjson.org/index.html>

3.2.3 Visualization

Requested visualizations are executed by Kibana. When a visualization is configured, it is periodically refreshed as new data is stored. Visualizations are grouped in dashboards (see Appendix H), which serves as the main page for further data analysis. In addition, Kibana includes *Developer tools* to request data with a JSON formatted query for fast search. Lastly, the *Discover* page shows the latest received data and basic statistics of incoming data to the Elasticsearch database and is used to monitor the received data frequency.

Chapter 4

Implementation

According to all specifications and speed requirements, the programming language will be C++, well compatible with netmap libpcap. The sensor will consist of a specific interface connection, packet parsing, logging and database connection. Referring to [Figure 3.1](#) the implemented component will be the sensor with external logging to files. The ELK stack is configured by respective configuration files and index creation via API call from Kibana developer tool or directly from remote host machine.

4.1 Sensor

Sensor implementation requires efficient multi-threaded solution, where each component will be viewed as an object (see [Figure 4.1](#)). The main requirement - configuration file, will have a standard Linux white space separated format (e.g. `/etc/hosts` file) with allowed bash style comments. The Configuration class loads the configuration file from the `/etc/sensor/` directory to specific C++ structures - `filter_config`, `db_config`, `iface_config` and validates the file's format. Components `Interface_connection` and `Database_control` are created with corresponding configuration structures, which contents are verified by connection attempt to database system, opening given interface file descriptor with specified filters. If any errors occur the message is logged and process terminated.

4.1.1 Configuration file

Configuration file must be located in the designated directory for program configurations (`/etc/sensor/conf.d/test.conf`). The main configuration file `/etc/sensor/sensor.conf` will hold path to configuration files (see [Listing 4.1](#)).

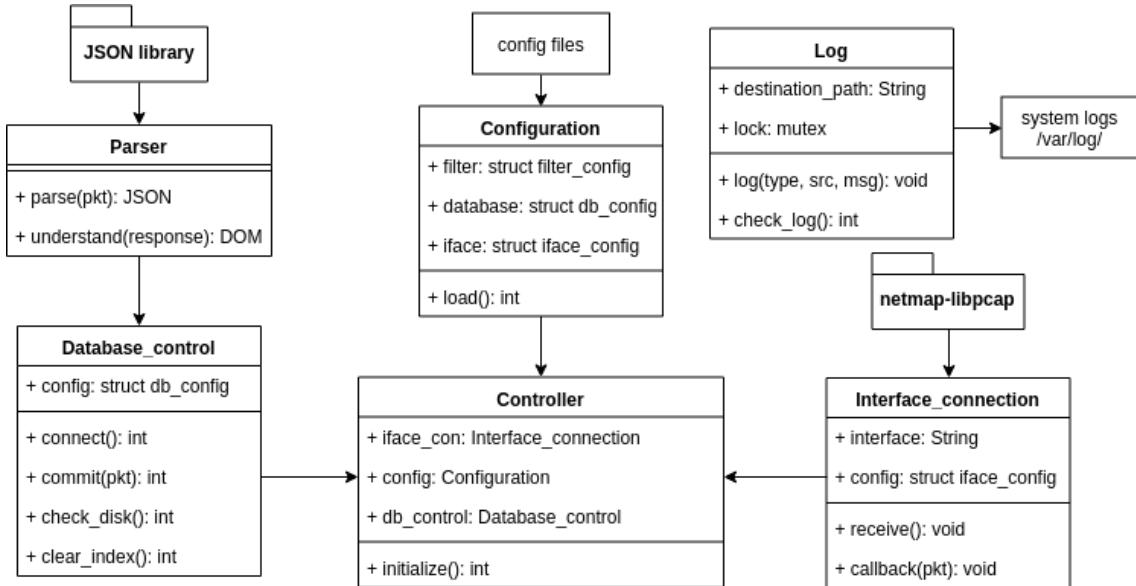


Figure 4.1: Class model of the implemented sensor

1 /etc/sensor/conf.d/*.conf

Listing 4.1: Contents of main configuration file

The configuration will be loaded on sensor startup and each line is loaded to corresponding data structure. Validations of configuration file will be logged to specific sensor log file. The configuration file must include the following fields. The source interface name must correspond to the name listed by *ip link* or *ifconfig* commands. The possible capture direction modes are "out" for outgoing packets, "in" for incoming packets and "promisc" for promiscuous mode. Packet capture filters are not compulsory, because they slow down the capture process. Nevertheless the allowed syntax is specified by the Berkeley Packet Filter syntax¹. The Filebeat and Elasticsearch connection specification must be a resolvable host IP address or host name and port must be a numbering ranging 0-65535. Archive path, must be an existing path on the local file system, where all summarized data will be archived. Archivation is limited by the *archive_limit* specified in mega bytes, when the index will be archived and cleared.

In case of missing component, the system will log it as an error and request correction. For sample configuration and default configuration refer to the [Listing I.1](#) in the Appendices section.

¹<https://docs.extrahop.com/7.2/bpf-syntax/>

4.1.2 Packet capturing

Netmap does not change the modified libpcap from programmers point of view. Packet capturing implementation consists of opening a file descriptor, applying filters to each received packet and opening a loop capture session (see Listing 4.2). After initialization of the *Interface_connection* class, the main packet receiving method will be a running thread in the *Controller* class.

```
1 struct bpf_program bpf;
2 bpf_u_int32 ip_addr, netmask;
3
4 pcap_lookupnet("eth1", &ip_addr, &netmask, error_buf);
5 pcap_t *handle = pcap_open_live("eth1", BUFSIZE, 1,
6 1000, error_buf);
7 pcap_compile(handle, &bpf, "dst 8.8.8.8", 0, ip_addr);
7 pcap_setfilter(handle, &bpf);
8
9 pcap_loop(handle, 0, callback_fnc, NULL);
```

Listing 4.2: Libpcap capture code sample

All packet capture relying data is provided by the configuration file specifying the interface used, capture direction and filters.

4.1.3 Packet parsing

RapidJSON library provides the *Simple API for XML* (SAX API), which includes a JSON generator *Writer*. Writer converts keys and values into JSON in a procedural manner (see Listing 4.3). The parsing is part of *Parser* class and its main parse function takes a libpcap packet structure provided by the caller (*Database_control* class). Keys specified in the output JSON must correspond to the Elasticsearch database mapping field names. Parsing is expected to execute without errors, since the input is a libpcap packet structure and the output is a JSON string.

```
1 using namespace rapidjson
2
3 StringBuffer = json_pkt
4 Writer<rapidjson.StringBuffer> writer(json_pkt)
5
6 writer.StartObject();
7 writer.Key("ip.src");
8 writer.String("100.154.25.6")
9 writer.Key("ip.dst");
```

```

10 writer.String("78.56.1.236")
11 writer.EndObject();
12 // json_pkt == {"ip.src": "100.154.25.6", "ip.dst":
    "78.56.1.236"}

```

Listing 4.3: Packet parsing to JSON format

4.1.4 Committing packets to ELK stack

Connecting to the database system is part of the *Database_control* class. The connection parameters, including the Filebeat public IP address and the target port, are specified in a configuration file (see Listing I.1). The established connection with the ELK stack component Filebeat, will provide a TCP stream of raw JSON data. Committing is expected to fail if the connection with Filebeat is lost, which will be properly logged. Successful commit will not be logged, because of the high frequency of commits. Sending data to Filebeat needs to be as fast as it was received and it will require another live libpcap session to send raw TCP data packets. The *Parser* class provides the JSON data of the received packet to the *Database_control* class.

This class receives packet structures from the packet capturing thread, running in the *Controller* class, which has a running thread of committing packets to the database system. That is the multi-threaded part of the sensor.

4.1.5 Checking disk usage

In a separate thread, running in the *Controller* class, the *Database_control* class has a function monitoring the disk usage directly on the Elasticsearch node, whose connection specifications are read from the configuration structure. It will log the current database state (number of documents and disk usage) and check for low free space.

```

GET "/elastic/bp:9200/_cat/shards?v"
[Sample output]
index shard rep state docs store ip           node
bp-test 2      r    STARTED 76661 415.6mb 10.0.0.1 Andromeda

```

Listing 4.4: Get number of documents and disk usage

When the free space gets low, specifically under a specified limit, a periodic function (see simplified code sample in Listing 4.5) checks for such scenario and executes specific tasks.

```

1 while (1) {
2     elastic = db_config.host + ":" + port;

```

```

3 // mark the latest document's date
4 latest_date = get_latest_date();
5 current_size = get_current_disk_size(elastic);
6
7 // check disk space
8 if (current_size < db_config.size_limit) continue;
9
10 // execute number of static and dynamically provided
11 // requests
12 // stores the request responses to specified path
13 summarize_index(elastic, db_config.archive_path);
14
15 // delete index by query
16 clear_index(elastic, latest_date);
17 sleep(CHECK_RATE);
18 }
```

Listing 4.5: Simplified *check_disk* function

Provided requests can be modified or created as a valid JSON formatted Elasticsearch GET API request query. The main configuration file */etc/sensor/requests.conf* will hold path to request files (see Listing 4.6).

```
1 /etc/sensor/requests.d/*.conf
```

Listing 4.6: Contents of main requests configuration file

The validity of GET requests is checked by Elasticsearch and received errors are logged. Additional GET requests must be tested on Elasticsearch beforehand, because there will be no warnings, besides the logs.

Deleting documents by query, queries the index and removes all matched documents. The deleted portion of index frees up space without interfering with frequent data storing. The summarized data in request responses will be stored in the archive path in parsed structure (parsing JSON to readable data using *Parser* class). According to the *class model*, the *understand* function returns a Document Object Model (DOM) object, which is a JSON parsed to C++ compatible object. Each archive file name will comprise of a timestamp and brief contents description distinguishing all archives.

4.1.6 Logging

Logging to */var/log/sensor/* directory will be handled by the *Log* class. Logs will be structured including the event's timestamp, log message level, log's source and the raw message (see *log* function in Figure 4.1). The timestamp will be marked in the *Log* class and other parameters will be passed by

the caller object. Message level will be statically listed in the *Log* class as an enumeration. For scalability purposes, each class utilizing logging will have a custom source identifier distinguishing it in the log file.

The existing message levels are informative, warnings, errors or debugs. *INFO_LOG* notifies successful operations or messages of informative manner. *WARN_LOG* includes warning messages, which are avoidable, but a fix is advised. *ERROR_LOG* message often comprises of the exception message caught at sensor start up and object initializations. *DEBUG_LOG* describes an optional output in the log file.

Since, multiple sources will log to the same file, the *Log* class has a *mutex* lock object to handle mutual exclusion of the shared log file. On sensor start up or every 24 hours the log file size will be checked (see Listing 4.7). If the size exceeds 10 MB, it will be archived in the same directory and compressed using the *gunzip*² compression tool by an OS system call (log rotation). The *check_log* function will be running in a thread under the *Controller* class.

```

1 while (1) {
2     current_log_size = get_log_size(destination_path);
3     if (current_log < LIMIT_SIZE) continue;
4
5     // using ctime library
6     time_t now = time(0);
7     tm *ltm = localtime(&now);
8     current_date = std::to_string(ltm->tm_year + 1970)
9         + "-" + std::to_string(ltm->tm_mon)
10        + "-" + std::to_string(ltm->tm_mday);
11
12    // use mutex to block logging while archiving
13    unique_lock<mutex> lock(mutex);
14    // archive current log file
15    logfile = destination_path + "/current.log";
16    archivefile = destination_path + "/current_" +
17        current_date + ".log";
18    system("mv " + logfile + " " + archivefile);
19    system("gzip " + archivefile);
20    system("touch " + logfile);
21    lock.unlock();
22    sleep(WHOLE_DAY)
23 }
```

Listing 4.7: Simplified *check_log* function

²<https://www.gzip.org/>

4.2 ELK stack setup

The deployment of the ELK stack on a server will be handled by series of *Ansible*³ scripts. It will install each ELK stack component, including setting up required configuration files. Every component configuration is described in the following subsections.

4.2.1 Elasticsearch

Configuring Elasticsearch requires setting up a new index for data (see [Listing 4.8](#)) and filling out the configuration file located in `/etc/elasticsearch/elasticsearch.yml` (see [Listing 4.9](#)). It can be created after correctly configuring Elasticsearch via `curl` program or via Kibana developer's tools.

```
1 PUT new_index
2 {
3     "settings": {
4         "number_of_shards": 3,
5         "number_of_replicas": 1
6     },
7     "mapping": { "_doc": { "properties": {
8         "source": {
9             "properties": {
10            "ip": { "type": "ip" },
11            "asn": { "type": "integer" }
12        }
13    },
14    "classification": { "type": "keyword" }
15  }
16 }}}
```

[Listing 4.8](#): Sample of creating an index in Elasticsearch

The mapping of the index needs to include all fields. The proper way is to design it in object form (e.g. `source` object mapping in [Listing 4.9](#)). Mapping will correspond to real life data types, meaning an IP address has the type `ip` or a geographical coordinates is of type `geo_point`. All mapping data types are listed in the Elasticsearch documentation⁴.

```
1 cluster.name: "sensor_cluster"
2 node.name: "main_db"
```

³<https://www.ansible.com/>

⁴<https://www.elastic.co/guide/en/elasticsearch/reference/current/geo-point.html>

```

3
4 path:
5   logs: "/var/log/elasticsearch"
6   data: "/var/data/elasticsearch"
7
8 network.host: "0.0.0.0"
9 http.port: "9200"

```

Listing 4.9: Elasticsearch configuration in YAML format

Path.logs and *path.data* specified the logging base directory and the path to archived index data respectively. Most important is the *network.host* in the example, which specifies that any remote system can access the database at specified port. This security vulnerability will be resolved by a firewall setting on the ELK stack server, allowing only the sensor host and localhost connections.

4.2.2 Filebeat

Filebeat will be configured with a host IP address and a port accepting TCP data. The JSON decoder in Filebeat is notified of receiving JSON formatted data via a tcp stream. All received data will be logged to corresponding log file. The output stream will be forwarded to Logstash socket specified by *output.logstash.hosts* (see Listing 4.10). In the background, filebeat harmonizes the data by various fields.

```

1 filebeat.inputs:
2 - type: tcp
3   max_message_size: 20MiB
4   host: "0.0.0.0:12000"
5
6 json.message_key: tcp
7 logging.to_files: true
8
9 output.logstash:
10   hosts: "localhost:12345"

```

Listing 4.10: Filebeat configuration in YAML format

4.2.3 Logstash

Referring to the [configuration](#), Logstash will be set up to listen on an arbitrary port and tagging the input. The filter clause removes undesired

fields, and renames fields for data field misconception elimination. The original *source* field holds the host address of the the source system sending data to Filebeat. The nested json clause creates a JSON object of the *message* in JSON string type. Once the JSON object is created, the *message* field may be deleted and a final field will be added to mark the future document with an identification of the filter clause used. The output clause sets the forwarding destination, which will be Elasticsearch database API, target index and document type.

4.2.4 Kibana

Kibana is configured by a configuration file */etc/kibana/kibana.yml*. The default configuration (see [Listing 4.11](#)) from the installation is correct, since both Kibana and Elasticsearch will coexist on the same physical machine. After all configuration files are correctly set and the Elasticsearch index is created, ELK stack is ready to receive data. The received data can be recognized and visualized by Kibana after setting up the index pattern, timestamp field and optionally adding script fields seen only by Kibana. New index pattern will be created under Management → Kibana → Index Patterns only after the index occupies at least one document. The index pattern timestamp fields is set in the second step. Afterwards, under Discover choosing the correct index pattern and setting up auto refresh (top right corner) will show new received data (see [Figure 4.2](#)).

```
1 # Default Kibana server settings
2 server.host: "0.0.0.0"
3 server.port: "5601"
4
5 elasticsearch.url: "http://127.0.0.1:9200"
```

Listing 4.11: Kibana sufficient default configuration

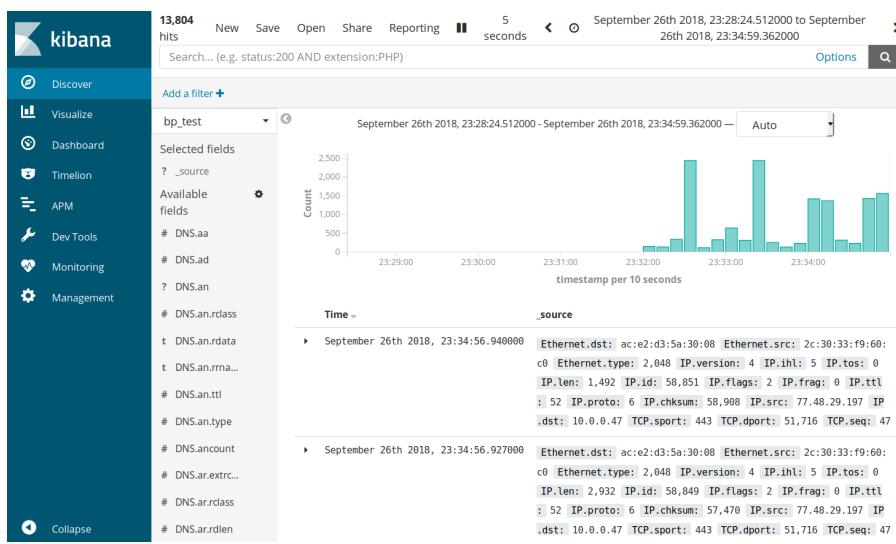


Figure 4.2: Kibana discover page of index `bp_test` with auto refresh and specific time period

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Appendix A

Bash script for drop rate

```
1  #! /usr/bin/env bash
2
3  test "$#" -lt 2 && exit 1
4
5  time="$1s"
6  iterator=$2
7
8  pcap=()
9  pfring=()
10 netmap=()
11 socket=()
12 scapy=()
13
14 while [ $iterator -gt 0 ]; do
15     echo "$iterator more loop tests.."
16     # PCAP
17     result=$(timeout $time ./pcap)
18     pcap+=("$result")
19     echo "$iterator:    $result - pcap"
20
21     # PFRING
22     result=$(LD_LIBRARY_PATH=/home/tomas/pfring/PF_RING/
23             userland/libpcap-1.8.1 timeout $time ./pfring)
24     pfring+=("$result")
25     echo "$iterator:    $result - pfring"
26
27     # NETMAP
28     result=$(LD_LIBRARY_PATH=/home/tomas/netmap-libpcap
29             timeout $time ./netmap)
```

```
28 netmap+="$result"
29 echo "$iterator:    $result - netmap"
30
31 # RAW SOCKET
32 result=$(timeout $time ./test_rawsocket)
33 socket+="$result"
34 echo "$iterator:    $result - socket"
35
36 # SCAPY
37 result=$(timeout $time ./test_scapy.py)
38 scapy+="$result"
39 echo "$iterator:    $result - scapy"
40
41 iterator=$(expr $iterator - 1)
42 done
```

Appendix B

Bash script for elapsed time

```
1 #! /usr/bin/env bash
2
3 test "$#" -lt 2 && exit 1
4
5 count=$1
6 iterator=$2
7
8 pcap=()
9 pfring=()
10 netmap=()
11 socket=()
12 scapy=()
13
14 while [ $iterator -gt 0 ]; do
15     # PCAP
16     result=$(./pcap $count)
17     pcap+=("$result")
18     echo "$iterator:    $result - pcap"
19
20     # PFRING
21     result=$(LD_LIBRARY_PATH=/home/tomas/pfring/PF_RING/
22             userland/libpcap-1.8.1 ./pfring $count)
23     pfring+=("$result")
24     echo "$iterator:    $result - pfring"
25
26     # NETMAP
27     result=$(LD_LIBRARY_PATH=/home/tomas/netmap-libpcap ./
28             netmap $count)
29     netmap+=("$result")
```

```
28 echo "$iterator:    $result - netmap"
29
30 # RAW SOCKET
31 result=$(./test_rawsocket.py $count)
32 socket+=" $result"
33 echo "$iterator:    $result - socket"
34
35 # SCAPY
36 result=$(./test_scapy.py $count)
37 scapy+=" $result"
38 echo "$iterator:    $result - scapy"
39
40 echo ""
41 iterator=$(expr $iterator - 1)
42 done
```

Appendix C

Linking various libpcap versions to one C source

```
1 root# gcc -o pfring test_libpcap.c /home/tomas/pfring/PF
   _RING/userland/libpcap-1.8.1/libpcap.so.1.8.1 -
   lpfring
2 root# gcc -o netmap test_libpcap.c /home/tomas/netmap-
   libpcap/libpcap.so.1.6.0-PRE-GIT
3 root# gcc -o pcap test_libpcap.c -lpcap
4
5 root# LD_LIBRARY_PATH=/home/tomas/netmap-libpcap ldd ./
   netmap
6 linux-vdso.so.1 (0x00007fff8fd0b000)
7 libpcap.so.1 => /home/tomas/netmap-libpcap/libpcap.so.
   1 (0x00007fc345fb2000)
8 libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0
   x00007fc345bc1000)
9 libnl-genl-3.so.200 => /lib/x86_64-linux-gnu/libnl-
   genl-3.so.200 (0x00007fc3459bb000)
10 libnl-3.so.200 => /lib/x86_64-linux-gnu/libnl-3.so.200
   (0x00007fc34579b000)
11 /lib64/ld-linux-x86-64.so.2 (0x00007fc3463f8000)
12 libpthread.so.0 => /lib/x86_64-linux-gnu/libpthread.so
   .0 (0x00007fc34557c000)
13 libm.so.6 => /lib/x86_64-linux-gnu/libm.so.6 (0
   x00007fc3451de000)
14 root# LD_LIBRARY_PATH=/home/tomas/pfring/PF_RING/
   userland/libpcap-1.8.1 ldd ./pfring
15 linux-vdso.so.1 (0x00007ffe22335000)
16 libpcap.so.1 => /home/tomas/pfring/PF_RING/userland/
```

```
          libpcap-1.8.1/libpcap.so.1 (0x00007f1fcraf42000)
17    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0
           x00007f1fcab51000)
18    libpthread.so.0 => /lib/x86_64-linux-gnu/libpthread.so
           .0 (0x00007f1fc932000)
19    librt.so.1 => /lib/x86_64-linux-gnu/librt.so.1 (0
           x00007f1fc72a000)
20    libnl-genl-3.so.200 => /lib/x86_64-linux-gnu/libnl-
           genl-3.so.200 (0x00007f1fc524000)
21    libnl-3.so.200 => /lib/x86_64-linux-gnu/libnl-3.so.200
           (0x00007f1fc304000)
22    libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2 (0
           x00007f1fc100000)
23    /lib64/ld-linux-x86-64.so.2 (0x00007f1fc40c000)
24    libm.so.6 => /lib/x86_64-linux-gnu/libm.so.6 (0
           x00007f1fc9d62000)
25 root# ldd ./pcap
26   linux-vdso.so.1 (0x00007fff365ee000)
27   libpcap.so.0.8 => /usr/lib/x86_64-linux-gnu/libpcap.so
           .0.8 (0x00007f393b7b0000)
28   libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0
           x00007f393b3bf000)
29   /lib64/ld-linux-x86-64.so.2 (0x00007f393bbf4000)
```

Appendix D

Hping3 traffic generator

```
1 hping3 command setup:  
2 hping3 -I eth0 --rawip -d 120 -i u<interval> 18.x.x.x --  
      rand-dest --rand-source  
3  
4     -d 120          --> include 120 bytes of data  
5     -i <interval>   --> set the interval in microseconds  
6     --flood          --> generate maximum number of packets  
7     --rand-source    --> set random source IP address  
8     --rand-dest      --> route packets to random destination  
      IP address  
9     18.x.x.x        --> specifies range of destination  
      addresses  
10  
11 testing script execution:  
12 ./test_mechanisms_droprate.sh 30 5  
13 30                  --> 30 second timeout for each mech  
14 5                  --> 5 iterations  
15  
16 intervals used:  
17 50000           --> 20      pkts/s  
18 5000            --> 194     pkts/s  
19 450             --> 2010    pkts/s  
20 32              --> 20050   pkts/s  
21 --flood         --> 179000  pkts/s
```

Appendix E

Packet capture graphs

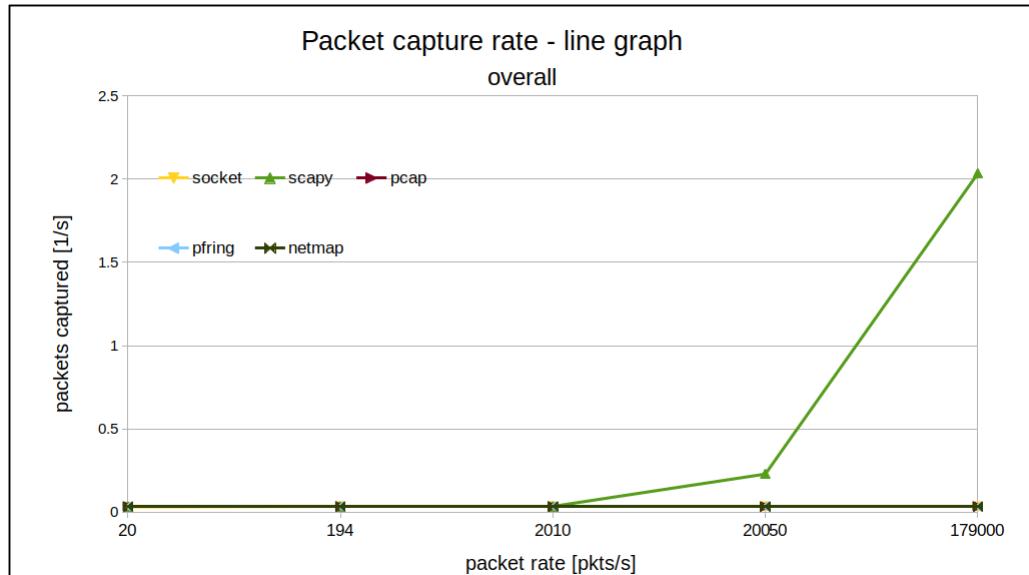


Figure E.1: Capture performance for testing drop rate

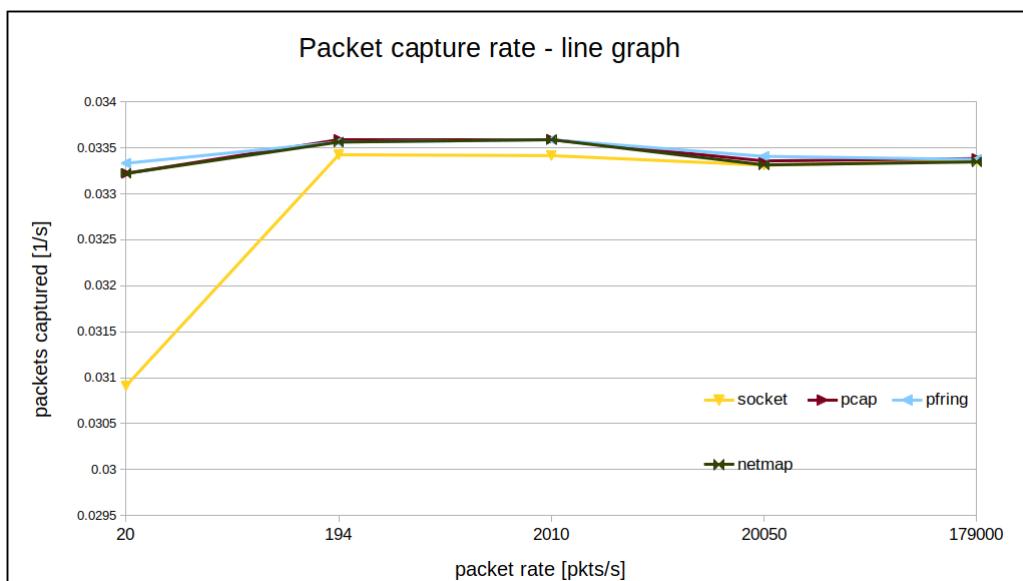


Figure E.2: Capture performance for testing drop rate. Number of packets captured in a second

Appendix F

Packet capture elapsed time

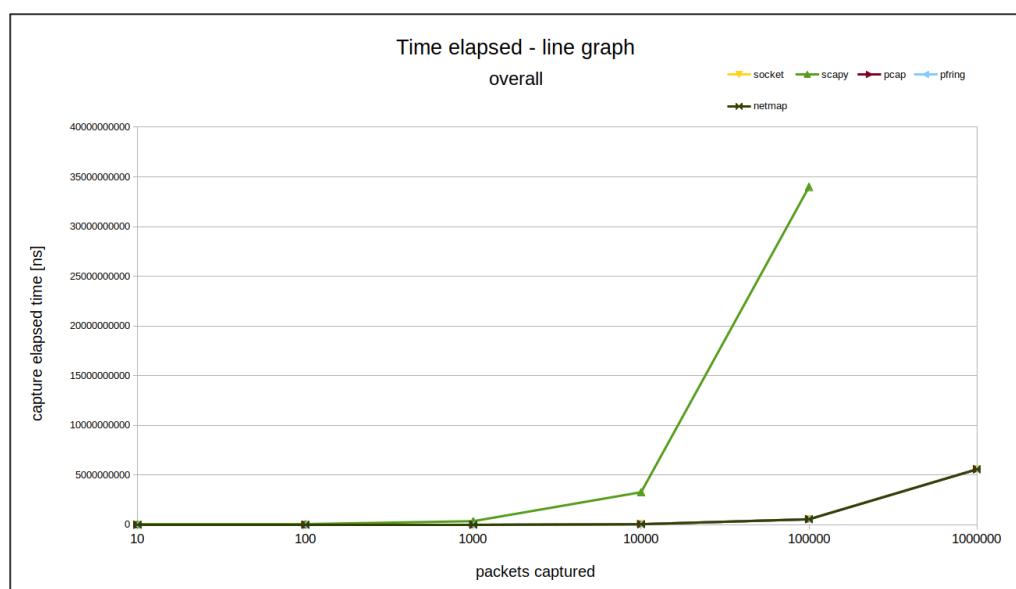


Figure F.1: Capture performance for testing elapsed time

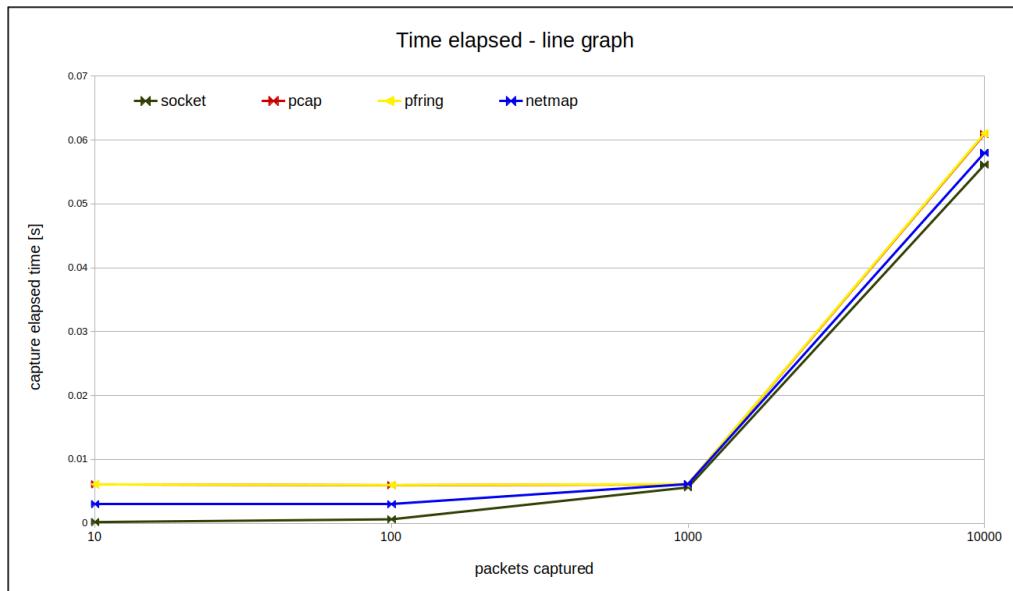


Figure F.2: Close up graph of capture performance for testing elapsed time and discarding scapy.

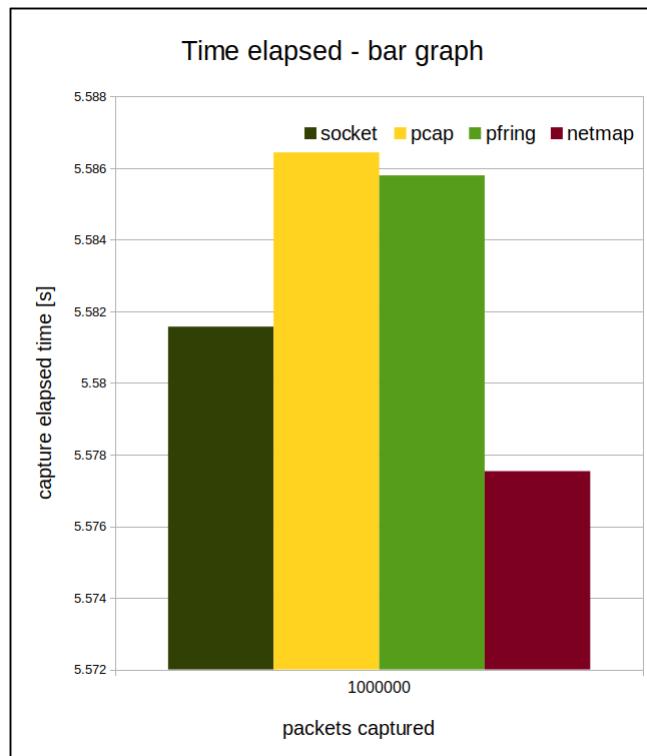


Figure F.3: Best performance at million sent packets

Appendix G

IIT.SRC research paper

Differentiating packet capture mechanisms in Proceedings of IIT.SRC 2019

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Abstract. This research paper, as a part of Bachelor's thesis, deals with analyzing various network traffic capture tools or libraries for Linux-based systems and choosing the most efficient one for real time network traffic. The main goal is to differentiate between native libraries (e.g. Libpcap), low-level protocol families (e.g. PF_PACKET/AF_PACKET, PF_RING) and other capture mechanisms with possible zero-copy/one-copy features, because efficiently keeping track of network traffic indications, is crucial for security and administrative reasons.

1 Introduction

The key difference in efficient network capture is

- the count of redundant copies of received packet data
- packet post-processing bypass
- buffers shared between kernel and user space.

Distinguishing the most efficient capture mechanism consisted of testing the elapsed time of capturing a static count of packets at consistent packet rate and testing for any drop rate of captured packets within a predefined time at various packet rates (packet capture efficiency). Testing network topology (see Figure 1) consists of two equal machines with following specifications.

- Operating system: Ubuntu server 18.04.2 LTS
- Ethernet Controller: Intel(R) 82579LM Gigabit Network Connection
- Process: Intel(R) Core(TM) i5-2500 CPU @ 3.30GHz, boost 3.70GHz, 4 cores

- Memory: 8 GB DDR3, 1333 MHz

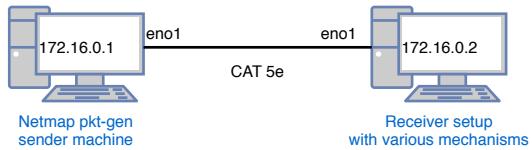


Figure 1. Testing topology

2 Packet capture

The most critical part is real time data capture in network traffic, meaning capturing network packets using a framework or capture library. It is a dependent process of hardware components like Ethernet Controller (NIC), processor performance and its properties (e.g. number of processor cores). Packet capture takes place in the NIC, but packet processing takes place in higher system layers, like the user space for Libpcap library. More efficient mechanisms share data from memory, which falls under the jurisdiction of lower system layer - the kernel space. Though, why is it more effective and efficient to access data in lower system layers? Kernel space is the operation system's (OS) core and an interface to hardware for the OS. More precisely, it is the access to shared kernel space buffers, which altogether bypasses the additional copying and processing present with basic frameworks not utilizing efficient features.

Received data on NIC is stored in NIC buffers. NIC registers keep track of whether the buffers are full and ready for reading or sending. This indication is handled by interrupts from the NIC to kernel. Kernel copies the buffer content to kernel space buffers (called *m_buffs* or *sk_buff*¹). These buffers are not

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¹ These kernel buffers are expensive to create and vary in size. They are complex and include large amount of metadata. [4]

accessible by user processes, but can be copied to the user space or the process accessible memory. This is a typical scenario

- two copies
- interrupts between kernel and user process to access received data on the NIC.

Possible improvements is to use, as mentioned previously, buffers shared between the kernel and the user space, which eliminates one or more copies and interrupts from kernel to user space, leaving only one copy between NIC buffers and shared buffers. Additional improvement is to have a NIC supporting multiple buffers, which splits the load and each buffer is handled by different core simultaneously [3].

A problem arises with the ability to capture all traffic on wire with no increasing delay resulting in packet loss due to lack of buffer space. Solution may be a zero-copy mechanism which utilizes a NIC dependent direct NIC access (DNA) feature or a one-copy mechanism, which utilizes the shared buffers.

3 Mechanisms

Tested mechanisms in scope of this research paper are

- *PF_PACKET*² protocol family
- standard Linux library *Libpcap*³
- open source framework *Netmap*⁴
- *PF_RING*⁵ protocol family by *ntop*

3.1 PF PACKET

A protocol family or file descriptor (FD) introduced to utilize the shared buffer is bypassing the Linux network stack and the packet socket FD receives full Ethernet frames. This packet socket is utilized by Libpcap since v0.6 release [5].

3.2 Libpcap

Standard Linux packet capture library utilized by Wireshark and Tcpdump. On datalink layer it captures packets with *PF_PACKET* and in its user space library it breaks down the packet to structures for further processing by the user process.

3.3 Netmap

Netmap targets the processing bottleneck in copying data from NIC to shared buffers. Netmap has its own *pkt_buffs* replacing standard *sk_buffs*, which are preallocated in comparison with *sk_buffs*' constant reallocations [3]. It includes *netmap* kernel module utilizing modified NIC driver kernel module.

3.4 PF_RING

On the socket layer it replaces *PF_PACKET*. It utilizes ring buffers in shared memory and modified NIC driver kernel modules and the *pf_ring* kernel module. Through Linux New API (NAPI)⁶ the kernel module copies polled packets from the NIC to shared ring buffers accessible by user application [2] Enhanced packet capturing is dependent of Intel NICs, but it works for other NICs too.

4 Performance testing

Setting up the testing environment consisted of two bootable Ubuntu server USB sticks with persistent storage. Both with installed Netmap framework with Netmap kernel module utilizing Netmap's patched NIC kernel module matching the original (see Listing 1). Machine generating packets (sender) was setup for running the Netmap's *pkt-gen*. Machine capturing packets (receiver) had, in addition to the Netmap framework, a compiled Netmap-based Libpcap and additionally had configured *PF_RING*, its modified Libpcap and installed corresponding library *libpfring*.

Listing 1. Netmap setup list of commands for NIC kernel module e1000e

```
sudo apt install linux-source
git clone https://github.com/
    luigirizzo/netmap dev/netmap
cd dev/netmap/LINUX
./configure --no-ext-drivers --
    kernel-sources=/usr/src/linux-
        source-4.15.0 --drivers=e1000e
make && sudo make install
sudo rmmod e1000e
sudo insmod ./netmap.ko
sudo insmod ./e1000e/e1000e.ko
```

² <http://man7.org/linux/man-pages/man7/packet.7.html>

³ <http://www.tcpdump.org/manpages/pcap.3pcap.html>

⁴ <http://info.iet.unipi.it/~luigi/netmap/> or <https://github.com/luigirizzo/netmap>

⁵ https://www.ntop.org/products/packet-capture/pf_ring/ or https://github.com/ntop/PF_RING

⁶ NAPI is a performance increase for packet capturing at higher packet rates, by enabling packet polling, therefore decreasing number of interrupts which otherwise would overwhelm the CPU [1]

Using *ethtool*, the network device features are disabled (-K option) for Netmap to correctly interact with its ring buffers. Secondly, the pause frames (option -A) are also disabled, which negotiate the allowed packet rx/tx frequency and therefore limits the receiving of transmitting process. (see Listing 2)

Listing 2. Machine network setup to maximize capturing for both machines

```
sudo ethtool -K en0 tx off rx off
          gso off tso off gro off
sudo ethtool -A en0 autoneg off tx
          off rx off
```

After setting up the sender, it could generate up to 1.389 million packets per second (Mpps) with exact options shown in Listing 3.

Listing 3. pkt-gen command executed on sender machine

```
sudo pkt-gen -i en0 -c 4 -f tx -l
       60 -w 3 -d 172.16.0.2 [-R <rate
>pps]
```

Table 1. pkt-gen options

option	description
-i	interface used
-c	number of CPUs
-f	function
-l	packet size
-w	wait for link time
-d	destination IP address
-R	packet rate

The receiver was setup with PF_RING as listed in Listing 4 and for both Netmap and PF_RING with compiled modified Libpcaps in their respected directories.

Listing 4. PF_RING setup list of commands for NIC kernel module e1000e

```
git clone https://github.com/ntop/
          PF\_RING dev/pfring
cd dev/pfring/kernel
make && sudo make install
sudo insmod ./pf_ring.ko
cd ../drivers/intel && make
cd e1000e/e1000e-* -zc/src
sudo ./load_driver.sh
# set up libpfring and libpcap
```

```
cd dev/pfring/userland/lib
./configure && make && sudo make
           install
cd ../libpcap && ./configure &&
           make
sudo make install
```

4.1 Packet capture efficiency

Testing the packet capture efficiency comprised of sender executing the pkt-gen command (see Listing 3) with

- rate of 1000 pps (see Table 2)
- and maximum rate of 1.389 Mpps (see Table3).

The receiver was capturing packets for 120 seconds and returning basic statistics of captured and dropped packets. For every capture mechanism the process was tested 5 times.

Table 2. Packet capture efficiency median results for 1000 pps

mechanism	packets captured	packets dropped
Libpcap	119963	0
PF_PACKET	120640	0
Netmap	119971	0
PF_RING	119964	0

Table 3. Packet capture efficiency median results for 1.389 Mpps

mechanism	packets captured	packets dropped
Libpcap	86880719	1003
PF_PACKET	117737210	9879085
Netmap	92077024	1143
PF_RING	21476253	0

Dropped packets is read from the mechanism's statistics output (e.g. *getsockopt* or *pcap_stats*), although considering that total packets sent was

$$1.389 \text{ Mpps} * 120 \text{ s} = 166.68 \text{ Mpks} \quad (1)$$

4.2 Elapsed time of captured packets

Testing the elapsed time (measured in nanoseconds) comprised of sender executing the pkt-gen command (see Listing 3) with no rate provided (resulting rate 1.389 Mpps) and on the receiver side changing the number of packets to be captured. The results are shown in Table 4.

Table 4. Elapsed time of captured packets with median results

mechanism	1K pkts [ms]	100K pkts [ms]	10M pkts [s]
Libpcap	2.292	140.531	13.847
PF_PACKET	5.060	505.313	50.768
Netmap	2.112	129.603	12.965
PF_RING	6.814	388.881	38.673

5 Conclusion

Referring to Packet capture efficiency (see Section 4.1) for the rather small packet rate all mechanisms captured 100% of generated packets. For the maximum packet rate the most packets were captured by PF_PACKET, which are raw Ethernet frames and would still require post processing. On the other hand Netmap-based Libpcap captured the most packets from the Libpcap-based mechanisms.

Although PF_PACKET captured to most packets in the previous test, it was not the fastest mechanism. Netmap managed to capture any number of packets tested in the shortest period of time (see Table 4). PF_PACKET could have been the fastest, but since measuring elapsed time was implemented in python, it might have influenced its performance.

Altogether, Netmap-based Libpcap has shown improvement to its native counterpart in both tests. PF_RING was surprisingly inefficient, which could have been due to improper opening of the network device in Libpcap. Worth mentioning are the native

APIs of both Netmap and PF_RING, which are much more efficient and worth further testing.

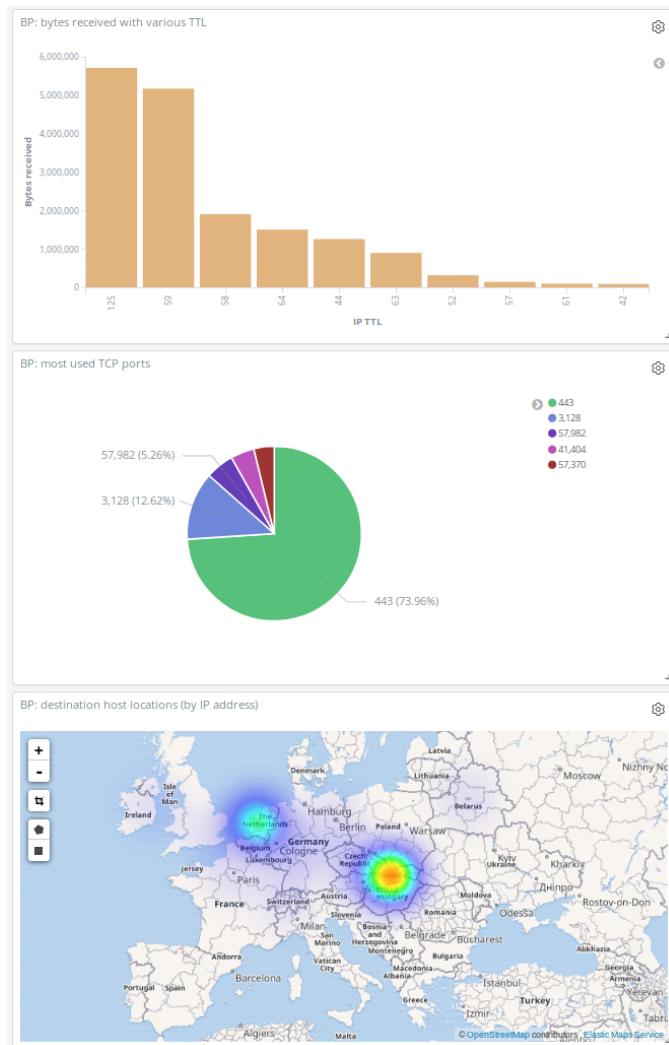
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Appendix H

Kibana dashboard



Appendix I

Sensor configuration

```
1 # contents of the /etc/sensor/conf.d/example.conf
2
3 # capture interface and mode
4 #default interface => not specified
5 interface      eth1
6 #default direction => promisc
7 direction      promisc
8
9 # filters as allowed traffic
10 # default => not specified
11 filter         src 10.0.100.56, dst 8.8.8.8
12
13 # Filebeat connection specification
14 # default host => localhost:12000
15 beats.host    192.148.56.4
16 beats.port    12000
17
18 # Elasticsearch connection specification
19 # default => localhost:9200
20 elastic.host  192.148.56.4
21 elastic.port  12000
22
23 # archive output path and archivation condition
24 # default => /etc/sensor/
25 archive_path  /home/user/sensor_archive/
26 # default => 10000 [MB]
27 archive_limit 50000
```

Listing I.1: Configuration example

Appendix J

Logstash configuration

```
1 input {
2     beats{
3         port => 12345
4         type => "bp_sensor"
5     }
6 }
7
8 filter {
9     if [type] == "bp_sensor" {
10        mutate {
11            remove_field => ["type", "beat", "input_type", "offset", "fields"]
12            rename => ["source", "_host_source"]
13        }
14        json {
15            source => "message"
16        }
17        mutate {
18            remove_field => "message"
19            add_field => { "_logstash_input_flow_id" => "bp_sensor" }
20        }
21    }
22 }
23
24 output {
25     if [_logstash_input_flow_id] == "bp_sensor" {
26         elasticsearch {
27             hosts => "localhost:9200"
```

```
28      manage_template => false
29      index => "bp_test"
30      document_type => "_doc"
31    }
32  }
33 }
```

Appendix K

Plan of work in winter semester

```
1 ===12.6.2018===
2 - My supervisor and I decided on using python.
3 - Look up a suitable library.
4 - Think about zero-copy (minimum number of copies)
    mechanims.
5 - Look up existing solutions.
6 - Test scapy + Redis and scapy + Elasticsearch.
7
8
9 ===20.9.2018===
10 - We discussed the structure of teh thesis.
11 - Redis is not a good choice for its efficiency decrease
    at data increase.
12 - Produce a prototype of scapy + Elasticsearch + Kibana
    visualizations.
13
14
15 ===1.10.2018===
16 - The prototype was a success and i can continue on
    developing Elasticsearch + Kibana.
17 - We discussed the possible visualizations.
18 - I continued imporving the prototype towards that end
    .
19 - Search for fast capture mechanisms.
20
21
22 ===8.10.2018===
23 - Begin performance testing of various capture
    mechanisms with hping3 traffic generator tool
```

```

24      - tcpdump, netsniff-ng, pfring-tcpdump
25  - Write thesis structure.
26
27
28  ===15.10.2018===
29  - Add other mechanisms for performance testing.
30      - raw socket, libpcap
31  - Both pfring-tcpdump and netsniff-ng have no drop rate
      oposing to tcpdump.
32  - Proper performance testing with capturing elapsed time
      and capture statistics.
33  - Create graphs representing mechansims' performance.
34
35
36  ===22.10.2018===
37  - Test pfring libpcap and standard libpcap libraries.
38  - Read about netmap framework.
39  - Scapy is not usable, since its performance it very
      poor.
40  - Netsniff-ng is also not usable, since its only a
      capture utility with no API.
41  - Raw socket is best so far (especially for low packet
      rate)
42
43
44  ===29.10.2018===
45  - Work on ELK stack (the database interface) and its
      performance.
46  - Implementa simple single libpcap program and compile
      it with all libpcap libraries.
47  - netmap-libpcap, pfring-libpcap, standard libpcap.
48  - Python is no longer the target programming language =>
      C/C===. 
49
50
51  ===05.11.2018===
52  - Linked multiple complied libpcap versions to a single
      libcpap program.
53  - Their performance is mostly comparable, but netmap is
      by far the best.
54  - We discussed the contents of multiple chapters of the
      thesis.
55  - Started writing analysis.

```

```
56
57
58 ===12.11.2018===
59 - Netmap provides a fast traffic generator (pkt-gen),
  but wasn't able to reach its full potential (9 Mpps).
60 - ELK stack performance is very low, but Kibana is very
  suitable program for visualizations and Elasticsearch
  has fast search.
61 - Possible theoretical improvemnet is to enlarge the
  Elasticsearch cluster by several nodes.
62
63
64 ===22.11.2018===
65 - Finished mechanism analysis.
66 - Started with performance testing description.
67
68
69 ===29.11.2018===
70 - Finished Analysis.
71 - Started with solution design.
72
73
74 ===06.12.2018===
75 - Finishing up with Design.
76 - Started on implementation outline
```

Appendix L

Plan of work in summer semester

```
1 ===11-02-2018===
2 - Start deploying functional ELK stack.
3 - Begin scripting Ansible automation
4
5
6 ===18-02-2018===
7 - Test automated (Ansible) deployment of the ELK stack.
8 - Begin programming the sensor (Controller class) and
    setting up its configuration file.
9 - Load configuration file to C++ structures.
10 - Configuration object verifying configuration file.
11
12
13 ===25-02-2018===
14 - Add test index for checking database connectivity.
15 - Implement the prototype Database class and Log class.
16 - Redirect error messages and other to log file.
17
18
19 ===04-03-2018===
20 - Start network capturing development of the Interface_
    connection class.
21 - Include Parser class with RapidJSON library.
22
23
24 ===11-03-2018===
25 - Include multi-threading between database control
```

```
        object and capturing object.  
26 - Insert first packet to the database.  
27 - Add complete packet parsing in the Parser class.  
28  
29  
30 ===18-03-2018===  
31 - Add monitoring features (check database disk space and  
      log file disk usage).  
32 - Parse Elasticsearch response JSON of summarized data.  
33 - Test delete_by_query API.  
34 - Test archiving log files and logging continuity.  
35  
36  
37 ===25-03-2018===  
38 - Add initialization logging and release alpha version.  
39 - Create exemplary visualizations in Kibana.  
40 - Version testing with various sensor configurations.  
41  
42  
43 ===01-04-2018===  
44 - Fix misconceptions and optimize program.  
45  
46  
47 ===08-04-2018===  
48 - Structure technical documentation.  
49 - Possible changes in program (optimizations).  
50  
51  
52 ===15-04-2018===  
53 - Final testing and documentation.  
54 - Start writing missing thesis sections.  
55  
56  
57 ===22-04-2018===  
58 - Empty week for corrections and finalization.  
59  
60  
61 ==29-04-2018===  
62 - Release version 1.0.0.  
63  
64  
65 ===06-05-2018===  
66 - Project deadline 07-05-2018.
```