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Implementation of High-Performance Network Interface Monitoring

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This thesis describes the development process of a monitoring solution that is capable of handling and crunching a vast amount of network traffic swiftly without impacting its performance. The goal of the project, as well as the requirement, was to capture the data without much or any loss. The project was done as a proof of concept as turning the data collection to a service was better option to extend the scalability of existing software solution.

The project started by drafting the initial sketch of the program architecture and agreeing upon certain features that were necessary. After initial planning was done it was time to set up the development environment and the required hardware. Only after the physical setup was properly running the programming could begin. The first parts of the programming consisted of getting to know the design patterns of asynchronous web servers and to study how to transfer data over the wire effectively. After some initial server drafts it was time to start studying the API provided by the hardware manufacturer. The API and the SmartNIC was the most important part of the project as it was responsible for capturing and handling the data.

The development of the program was split into parts and developed separately. The project began by developing the server and a client for testing purposes. After successfully sending and receiving data it moved forward to implementing the API and capturing data from the network.

In the end, the project reached such a state that it was able to receive parameters from the client application and start a monitoring session based on the parameters. It then proceeded to capture data matching the filter and sending it to the client packed in a Protocol Buffer. As a result, the project was deemed to be a success as a proof of concept.

Further development for the product can be done by improving the complexity of the filtering, as the SmartNIC offers wide range of tools to customize the filtering of the network traffic. Adjusting the filtering can provide more defined information about the state of the network and possible errors that are hampering the performance.

Keywords	Networking, C++, Monitoring

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Insinöörityön tarkoituksena on esitellä projekti, jonka aiheena oli verkon monitorointi. Tavoitteena oli kehittää ohjelmistoratkaisu, joka pystyy monitoroimaan suuria määriä verkkoliikennettä ilman minkäänlaista ongelmaa. Projektin tavoite sekä vaatimukset olivat, että kaapattu data pitää saada kiinni semmoisenaan, eikä sitä saisi kadota juuri laisinkaan. Projekti toteutettiin niin ikään näyttönä, jonka tarkoituksena oli lujittaa mielipidettä siitä, että datan kerääminen palvelumuotoisena applikaationa on parempi ratkaisu, kun pyritään skaalaamaan olemassa olevaa ohjelmaa suurempaan mittapuuhun.

Projektin alussa laadittiin erilaisia vedoksia ohjelmiston arkkitehtuurista sekä sovittiin, mitkä ominaisuudet ovat tärkeimpiä projektin onnistumisen kannalta. Näiden toimenpiteiden jälkeen aloitettiin kehitysympäristöiden asentaminen, sekä hankittiin tarvittavat laitteistot. Kun laitteistot oli asennettu, pystyttiin siirtymään ohjelmoinnin pariin. Ensimmäiset vaiheet ohjelmoinnissa olivat erilaisiin suunnittelumalleihin tutustuminen sekä datan lähettäminen ja vastaanottaminen kaapelin välityksellä. Ensimmäisten ohjelmaluonnosten jälkeen siirryttiin opiskelemaan laitevalmistajan toimittamaa ohjelmistorajapintaa. Tämä ohjelmistorajapinta oli SmartNIC:in lisäksi projektin kannalta kaikkein tärkeimmät seikat, koska ne olivat pääsääntöisesti vastuussa datan kaappaamisesta sekä sen käsittelystä.

Projekti jaettiin kahtia ja kumpaakin osaa kehitettiin erillään toisesta. Ensimmäisessä vaiheessa projektia pyrittiin kehittämään serveri sekä asiakasohjelma, joilla kokonaisuutta voitaisiin testata. Tämän vaiheen jälkeen siirryttiin työstämään ohjelmistorajapinnan käyttöä datan kaappauksessa.

Lopulta projekti oli saavuttanut sellaisen pisteen, jossa se pystyi vastaanottamaan ehdot monitoroinnin aloittamiseksi asiakasohjelmalta, sekä lähettämään noiden ehtojen mukaista dataa takaisin.

Jatkokehityksenä projektiin voidaan toteuttaa monimutkaisempia ja tarkempia suodattimia asiakasohjelman parametrien perusteella. Nämä tehokkaammat suodattimet voivat antaa tarkempaa informaatiota verkon mahdollisista vikatiloista sekä ongelmista.

Avainsanat	Tietoverkot, C++, Monitorointi

Contents

List of Abbreviations

SmartNIC	Smart Network Access Interface. A computer hardware component that enables the computer to connect to a network.
UDP	User Datagram Protocol. Allows computer applications to send messages to other hosts in the network.
TCP	Transmission Control Protocol. Main protocol in the Internet Protocol suite. Provides ordered, reliable and error-checked delivery of stream of octets.
SCTP	Stream Control Transmission Protocol. Networking protocol that operates at the transport layer and acts similarly to UDP and TCP.
RHEL7	Red Hat Enterprise Linux 7. A distribution of Linux targeted for commercial use.
TAP	Terminal Access Point. System that monitors the network events and provides aid in analyzing it.
SPAN	Switched Port Analyzer. Port mirroring is generally referred as SPAN in Cisco System's switches.
RSPAN	Remote Switch Port Analyzer. Same as SPAN but allows monitoring of traffic from source ports of multiple different switches.
MAC	Medium Access Control. Part of the Data Link Layer which controls the hardware that is responsible for interacting with the wire or wireless media.
LAN	Local Area Network. A computer network within a limited area that interconnects computers.
ASIC	Application-specific integrated circuit. An integrated circuit that is tailored for a specific purpose.
FPGA	Field-programmable gate array. An integrated circuit that can be configured by the user.

SOC	System on Chip. An integrated circuit that can contain all the necessary components of a computer or an electrical system.
IDE	Integrated Development Environment. Software application that provides an environment where to develop code. Often consists of at least a source code editor, build tools and a debugger.
STL	Standard Template Library. A set of common classes for C++ that influence many parts of the C++ Standard Library.
OS	Operating System. A software that handles hardware and software resources.
API	Application Programming Interface. A clearly defined set of functions and methods used to interface two components.

1 Introduction

The services and functionalities of today's life are built upon a complicated network structure that is constantly changing and evolving to allow more and more connections with ever increasing transfer speed. Transactions and communication flow through the wire and even a slightest disturbance in the connectivity can cause severe issues in daily routines of the users.

Monitoring the state and the performance of the network is important to guarantee the best possible service to the users. Different monitoring techniques and solutions have been developed to diagnose issues in connectivity, such as monitoring software or even physical devices that are connected to the wire. Depending on the selected monitoring solution there can be noticeable degradation of the service or other issues such as packet loss.

The purpose of this thesis was to explore different monitoring options and describe the design and implementation of a project that was used to monitor high speed connections in mobile networks. The project was planned to be a part of a larger software structure and a proof of concept. The goal of the project was to separate the data collection from existing software and turn it in to a running service that could reliably provide the requested monitoring data to the client.

Due to the vastness of the project, the thesis focuses mainly on implementing the data capture and processing and partly covers the data transferring between client and the server.

2 Overview

The project served as a proof of concept and was done for Nokia. The purpose was to separate data collection from an existing software solution and turn it in to a data collector software that was able to answer requests from other programs or client applications. The data that could be requested was limited at the beginning, but it could easily be expanded within the capabilities of the network card. The card that was used in the project is produced by Napatech. It is part of the Smart Network Interface Cards (SmartNIC) family and it is capable of processing large chunks of data segments rapidly. It offers wide range of useful features to handle incoming traffic while still having negligible impact on the performance of the network.

Monitoring the network is important because it provides vital information for different issues. For example, the monitoring data can be used to pinpoint a malfunctioning base station in the mobile network or use the data to develop machine learning algorithms. The SmartNIC provides multiple different ways to define which type of data is to be captured. The project was initially interested in capturing only UDP, TCP and SCTP data.

The program that was developed and described in this thesis was written in C++ utilizing drivers and libraries provided by Napatech, as well as Boost and some third-party libraries. The final product was planned to be used in UNIX environment. The main development tools were Microsoft Visual Studio 2017, CMAKE and a server running Red Hat Enterprise Linux 7 (RHEL7).

2.1 Motivation

While every year connectivity increases as more and more items are introduced to the network and can transmit data, providing proper tools to maintain and monitor those networks become increasingly important. The motivation for this thesis came from the desire to learn how networks operate and how data could be transferred securely and effectively over the wire.

3 Background

Network monitoring is important as it provides vital information to administrators of the network in case there is an anomaly in the performance. The monitoring could be implemented by using a Network TAP (Terminal Access Point) or a port mirroring. Both have their time and place as well as strengths and weaknesses. A probe is best described as a program or device that utilizes the received data from a TAP and visualizes or otherwise processes it to provide useful information.

This section of the thesis covers some of the existing monitoring solutions and how they function, how the network layers are stacked and what they do and how does the SmartNIC compare to ordinary NIC. These are important concepts to grasp prior to developing a monitoring application.

3.1 TAP

A Network TAP is often a dedicated hardware device, which is inserted in the network. It is installed between the device that is to be monitored and the network. When the packets arrive to the monitored device, the TAP copies them and sends the copies to probes or analytics systems. This monitoring solution has existed for a long time. During the early days of the network it was done for the copper wires. Nowadays it is done for the optic fibers.

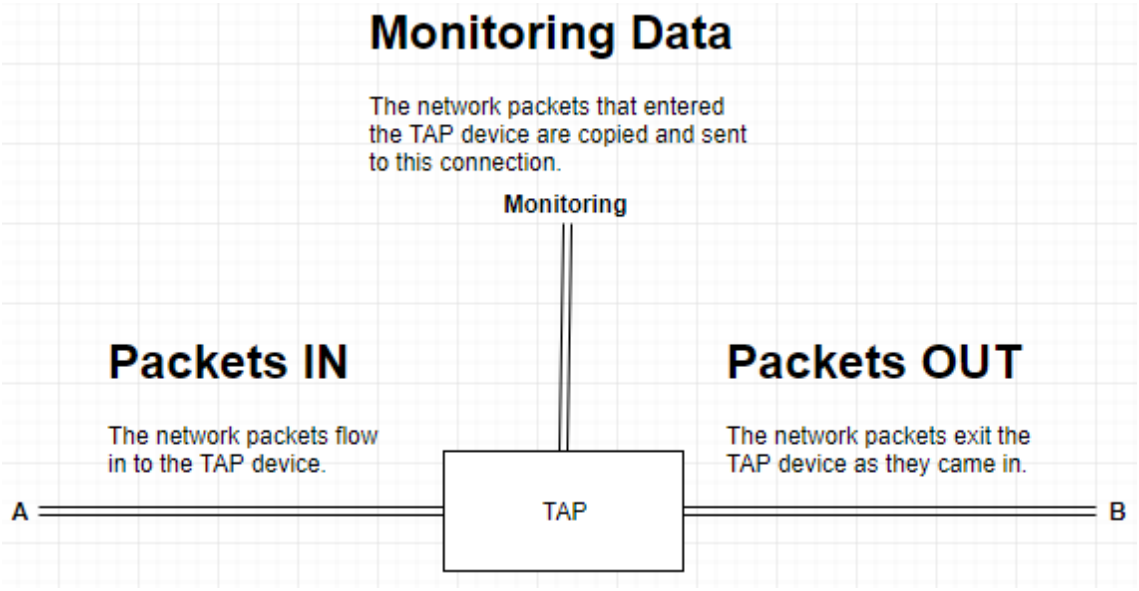


Figure 1. Diagram displaying TAP device with three ports.

The TAP device consists of at least three ports: A, B and monitoring port. In Figure 1 the TAP device copies the packets in the AB wire to the Monitoring wire. This is the simplest form of TAP since it only copies the data. More complicated version of TAP could perform, for example filtering and send only the requested packets to the Monitoring wire. Placing the TAP as a monitoring device in the network can introduce unwanted interactions. If the device crashes or is booted, the network will stop as it is installed in-line.

The physical TAP device can be switched to a Tapping system to counter the issue of crashing the network if the device encounters an error or is rebooted. From Tapping systems, V-Line Tapping is the most important, as it allows the network to continue operating even if the TAP is not operational at the time. In V-Line Tapping, the system is installed in-line but it keeps sending heartbeat packets to the system at the end of the Monitoring wire, to check if it is still available. If the TAP does not receive heartbeat acknowledgement from the system, it enters a bypass mode in which it directs the traffic normally from A to B. However, if the system responds to the heartbeat the traffic is copied over to the Monitoring wire.

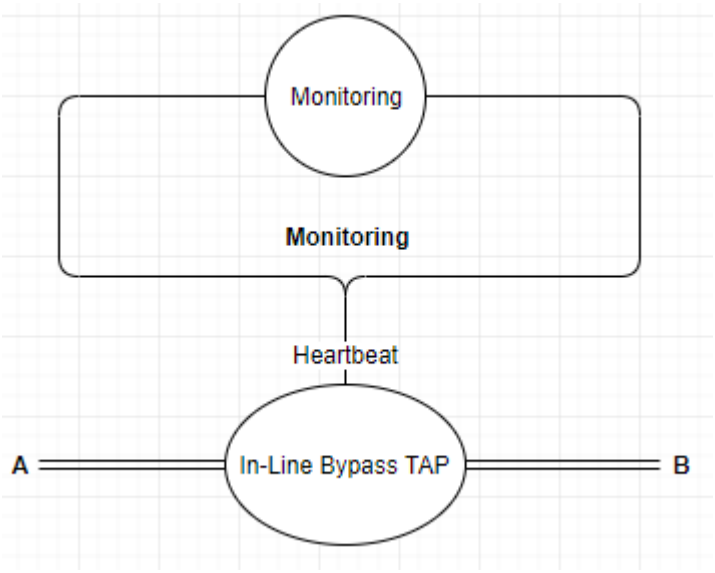


Figure 2. In-Line Bypass TAP with a Monitoring system

In Figure 2, if the Monitoring system (depicted as a circle) does not respond to the heartbeat packet, the TAP triggers the Bypass mode and stops sending traffic to Monitoring wire. The TAP continues to send heartbeats to the Monitoring system in case it becomes active again.

The benefits of using a TAP to monitor a network lie in the reliability. TAP eliminates the risk of dropped packets and received all the traffic, including physical errors. It also provides complete visibility into full-duplex networks as it transmits both the received and sent data simultaneously on separate channels. Downside of implementing a TAP solution are the costs that increase when higher levels of OSI model are required to be monitored.

The internal hardware of TAPs contains often different type of splitters that do what the name implies, split the signal. An optical splitter is used with optical fiber connections and copper TAPs are used with original twisted pair cables. As the name suggests, an optical splitter operates on signals generated by light and copper splitters operates on signals generated by electricity.

Traditionally the light in the optical fiber is split fusing two cables together in a such way that the light carrying the signal is partially funneled off to the second cable. This method is called Fused Biconical Taper (FBT). Another type of splitter uses thin film technology

which takes advantage of reflections. A light is basically shone through a window and a portion of that light is reflected.

3.2 Port mirroring

Port mirroring is a process where the network switch sends a copy of network packet received in one port, to another switch port which is used to monitor the network. In Cisco Systems switches port mirroring in referred to Switched Port Analyzer (SPAN) or Remote Switched Port Analyzer (RSPAN). Each switch manufacturer has their own name for the technology.

According to Cisco's documentation regarding port mirroring, SPAN is an important configuration in a switch to ensure that the probe can receive the traffic. Compared to a hub which sends the incoming traffic to all ports, switch learns the destination MAC addresses and forwards traffic only to ports that corresponds to the right MAC. Therefore, the probe does not receive any traffic, except traffic that is flooded to all ports. [1] If the switch does not know who should receive the data, it will send it to all connected ports and leave it up to the receiving end to decide if the data is meant for them. In this case the sniffer will receive the data.

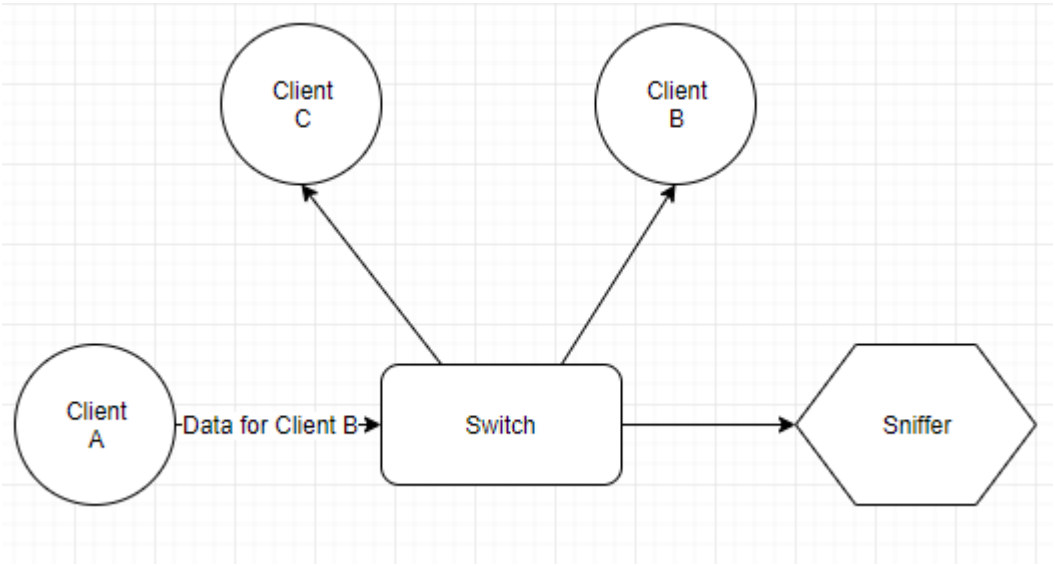


Figure 3. The switch does not know the MAC address of Client B and therefore sends all traffic to connected ports.

Figure 3 demonstrates the case where the switch has not learned all the MAC addresses and will flood the traffic to all ports. When the correct recipient of the data is learned, the MAC address of that client is added to the switch's routing table and further traffic pointed to that address is automatically forwarded.

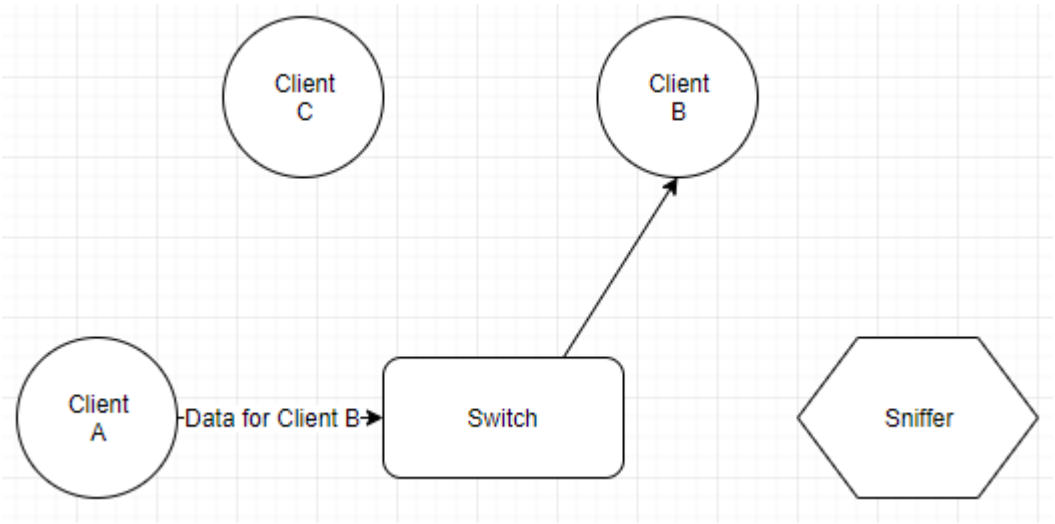


Figure 4. The switch knows that the data from Client A is meant for Client B and forwards it straight to the correct recipient.

In Figure 4 the switch is aware of Client B's MAC address and can forward the data directly to it without needing to flood it to every connection. This data is undetectable to the sniffer.

Compared to TAP, port mirroring is a low-cost solution and remotely configurable as the network switches are often configured to be accessible remotely. If the network traffic becomes too intense, SPAN might start dropping packets to keep pace with the traffic. It also requires more from the switch, as it now needs to copy the traffic to a designated monitoring port.

3.3 Probe

Probe is a device or a software that is used to extract metadata from the network traffic which is received from a TAP or a SPAN. Probes are mainly used for troubleshooting the network issues, for visualizing the traffic and for providing insight for the administrators.

Network probes can operate either passively or actively. Passive probes do not generate any traffic in the network as they just receive the packets and process them. Active probes are mainly used for end-to-end monitoring between different nodes and requires an active probe to generate data, which is then received by another probe. The performance of the network is monitored and assessed from the results generated by probes.

3.4 Open Systems Interconnection model

The development of the Open Systems Interconnection model (OSI model) was started in 1977 by the International Organization of Standardization (ISO). They noticed that there was an urgent need for standards in network communications to allow creation of heterogenous informatic networks. Even though experimental computer networks, such as ARPANET, had already been under development and considered to be heterogenous, each manufacturer had their own way of connecting their equipment. This resulted in a situation where equipment from two different manufacturers were incompatible or required hard work, when it came to be connecting these two pieces so that the communication functioned correctly. [2, p. 425]

Open Systems Interconnection model (OSI model) is a conceptual model which describes the standardized way the communication should be conducted in the network. The model consists of seven layers, each serving to the layer above. The seven layers of the model from the lowest to the highest are as follows: Physical, Data Link, Network, Transport, Sessions, Presentation and Application. Each layer has a specific task and set of protocols that is unique to that layer.

When data passes through the stack it is handled as a protocol data unit (PDU). Each of these protocol data units contain a payload which called service data unit (SDU) and protocol-related headers. For example, when the data starts from the application layer and proceeds down the stack, each layer concatenates the encapsulated data with a header related to that specific layer. When the data reaches the lowest level, it is transmitted to the receiving device. The data then moves up the stack as a series of service data units as the layers strip the headers away, passing only the contained payload up to the next level.

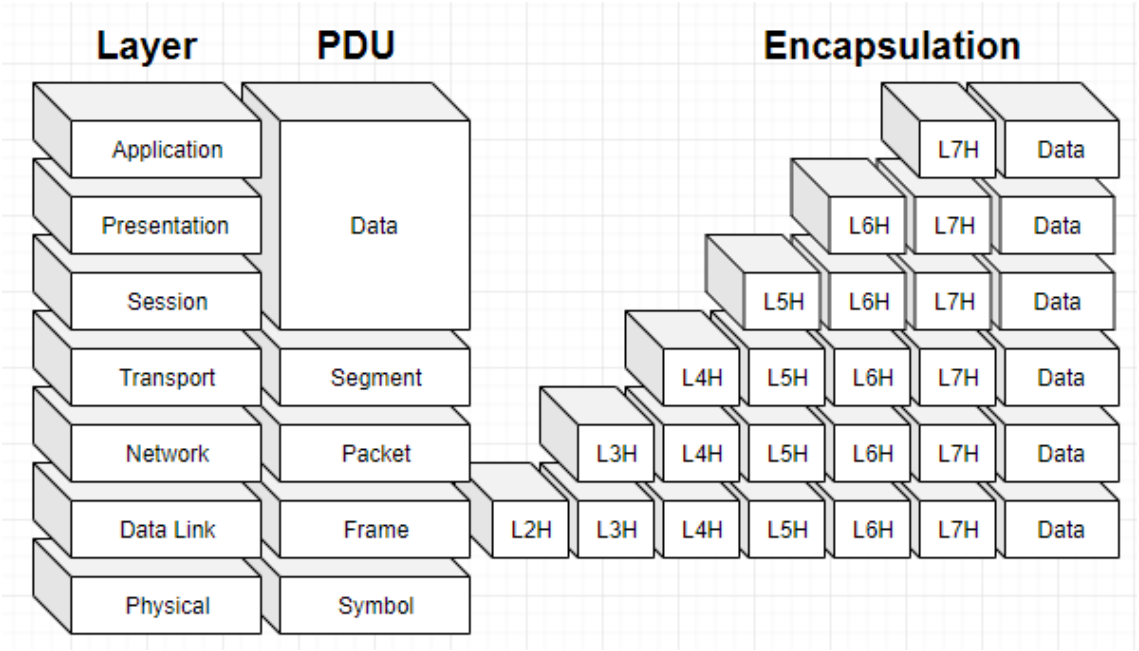


Figure 5. Layers, corresponding PDU and the number of headers in encapsulated data for each layer.

Figure 5 illustrates the stack of the OSI model and displays the corresponding PDU next to the layers. The encapsulation demonstrates the number of headers for each layer, as the data flows down from the application layer towards the physical layer. Physical layer

does not apply any headers of its own as it is responsible for transmitting the data instead of further encapsulating it.

Three of the lowest levels of the OSI model (Physical, Data Link, Network) are grouped as Media layers. They are responsible for sending and receiving the data as well as making sure that the transmitting and receiving happens. Physical layer handles the hardware level operations that include mechanical and electrical operations. It receives and transmit the data in its rawest format, as electrical, radio or optical signals.

The data link layer receives the data from physical layer, detects possible errors in it and tries to correct them. It handles the data frames and their transmission between two nodes that are connected by the physical layer.

The network layer hides all the oddities from the next layer (Transport) as it does not need to be concerned with the actual transfer medium. This way the network layer provides independence from relaying and routing considerations as well as from the data transfer technology. The data transferred at this layer can be of varying length. If the length of the data to be transmitted is too large, it can be chopped to smaller segments that are then transmitted and constructed on the receiving end. Data sequences at this layer are called packets.

Transport layer provides transparent transfer of data between the end systems. By providing reliable and efficient data transfer, the upper layers can focus solely on their own functionality. Transport layer can tract the segments that it transmits and therefore retransmits the segments that fail delivery.

The session layer handles the establishing, management and termination of connections between applications. These applications can be local or remote. According to Huber Zimmermann in his paper OSI Reference Model – The ISO Model of Architecture for Open Systems Interconnections, the session layer provides services two types of services. Firstly, it can bind and unbind two presentation entities into a relationship. This service is called session administration service. Secondly, it controls data exchange, delimiting and synchronization operations between two presentation entities. This second service is called session dialogue service. [2, p. 430]

Presentation layer provides independence to the application process by allowing the application layer entities to use different syntax and semantics if the presentation layer provides the required mapping for them. John D. Day and Huber Zimmermann state in their paper, The OSI Reference Model, that the presentation layer's protocol allows the user to select a "Presentation Context". They continue to explain that the Presentation Context can be application specific, i.e. library protocol. [3, p. 1338]

The last of the layers, application layer, is the closes one to the end user. This means that both the user and OSI application layer interact directly with the software. Typical functions of application layer are for example determining available resources and synchronizing communication.

3.5 Network Interface Controller

Network Interface Controller (NIC, also known as Network Interface Card, Network Adapter, LAN Adapter or Physical Network Interface) is a hardware component that allows the computer to connect to a network. The NIC acts as both the physical and data link layer device. During the early days of the Internet the network cards were designed as extension cards that could easily be plugged in a motherboard. In the end, it was the ubiquity of the Ethernet standard combined with the low costs, which lead to including these networking capabilities directly into the motherboards. Nowadays these Ethernet capabilities come from chipsets integrated directly into the motherboard or from a low-cost dedicated Ethernet chip, making a separate network cards redundant unless there is a need for additional independent connections or the network uses some non-Ethernet type.

3.6 SmartNIC

SmartNIC (Smart Network Interface Controller) functions like a normal NIC but brings more to the plate in functionality. These SmartNICs go further than just simple connectivity and perform network traffic processing right on the card instead of requiring CPU to handle the processing. This lightens the load on the CPU when there is a need to inspect the traffic going through the card. SmartNICs come in different forms but the most common, if not the only, cards are ASIC, FPGA or SOC based. Each of these types

have their own strengths and weaknesses when developing programs that utilize them to their fullest.

ASIC stands for Application Specific Integrated Circuit. It is an integrated circuit (IC) that is designed and programmed to serve only a single purpose. Because it is tailored to perform a single operation efficiently it has amazing price-performance. ASIC based SmartNICs are easy to program and extend, but they are flexible only to their pre-defined capabilities.

FPGA is an abbreviation for field-programmable gate array, which is an IC that is configurable by the customer or a designer. The chip contains an array of programmable logic blocks that can be connected. These connections can be reconfigured when necessary. A single logic block can contain a complex combinational function or act as a simple logic gate. These chips are programmed using hardware description language (HDL). SmartNICs utilizing FPGA based design have a good performance but are rather costly. They are also harder to program when compared to their ASIC based counterparts.

SOC, System on Chip, integrates all components of a computer or another electronic system. This type of chip often includes a CPU, memory, secondary storage and I/O ports, all on a single small chip. SmartNICs based on this solution offer easily approachable programming tasks as well as high flexibility.

3.7 Selected solution

In the project the Napatech's SmartNIC was connected directly to the optical splitter, as there was no need to configure more complex setup. The data was split 90/10 between the project server and the original server, meaning that the project server received 10 % of the data and the original server 90 %. This solution was chosen as the server running the original software could not be disturbed. This setup allowed the project server to still receive the data that the original server was monitoring. Verification of the data became easier as both applications wrote were able to write the captured data to PCAP format. These capture files were then inspected with Wireshark and compared.

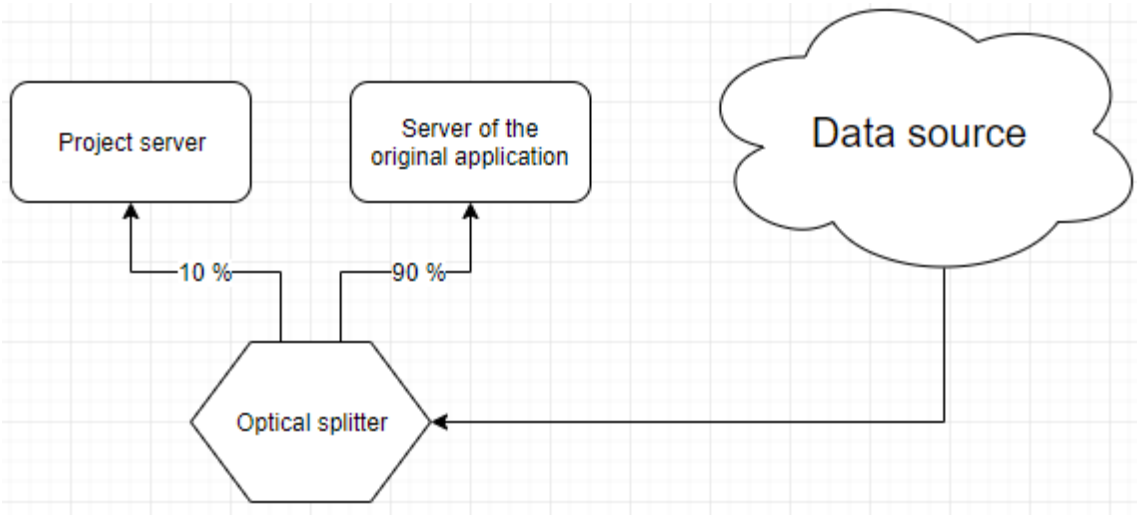


Figure 6. Configuration of the hardware.

Figure 6 above displays how the optical splitter was connected to the servers and the source of the data. If the splitter could not have been connected directly to the Napatech's SmartNIC, SPAN could have been used to monitor the in the project server. The SmartNIC used in the project was FPGA based.

4 Tools, libraries and classes

4.1 Microsoft Visual Studio

Microsoft Visual Studio was the chosen integrated development environment (IDE) for the project because of earlier experience from its use. It offered the possibility to remotely connect to UNIX based machine and upload and compile sources in that environment. When executing the program, the IDE acts as a front-end and displays in a console window the outputs of the program running remotely in the Linux server. This was a desired feature because the project was targeted for UNIX based environments and the development was done on a Windows machine. Debugging with Microsoft Visual Studio offered a valuable insight into the current variable states and what was running and in which thread. The possibility of debugging the program step by step made finding the errors and bugs much easier.

4.2 CMake

CMake is a combination of cross-platform tools that are designed to build and test software. Instead of writing complicated Makefiles, the CMake was chosen for this project due to its relatively ease of use. CMake's build process has two stages, configuration and generation steps.

During the configuration step CMake first looks for and read CMakeCache.txt, if it exists from previous runs. After that CMakeLists.txt is read from the root of the source tree given to CMake. These files contain the information how to generate the build files. Contents of these files are parsed by CMake language parser and it effectively "executes" the user-provided CMake code. After the code is executed and everything have been correctly computed, CMake generates CMakeCache.txt for further runs.

After configuration step is completed generation step starts and creates the build files for selected build tool. The generation step is much shorter and simpler than the configuration step as it involves only writing the build files, whereas configuration step checks for cache, reads files and writes cache.

4.3 MobaXterm

MobaXterm is a terminal tool that is ideal for remote connections. Originally the project started by using PuTTy, but the functionality it provided proved to be lacking in the long run. Some of the perks that the MobaXterm offered was SFTP browser to the currently connected SSH session, which allowed easily to move files between the remote server and local computer.

4.4 Wireshark

Wireshark is a valuable tool when one needs to analyze network traffic and protocols. It can capture live traffic or perform analysis offline. The displayed data can be filtered extensively based on protocols, IP addresses or such. Wireshark can read and write in many different capture formats and compress them with gzip. For this project it is used

as a debugging tool and a way to verify the contents of the messages sent between client and the server. The verification of the data was done by capturing simple UDP messages that were known beforehand, such as “Hello World”. The captured data was written in a PCAP file and then opened on Wireshark for closer inspection.

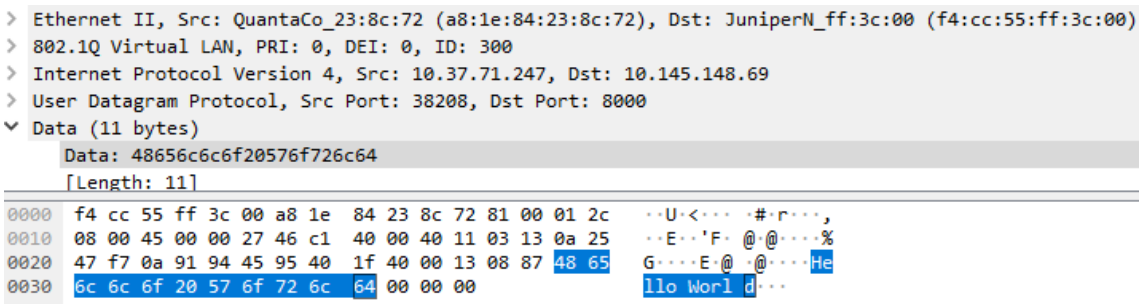


Figure 7. Inspecting the captured frame in Wireshark

In Figure 7 the captured frame is inspected closer. Wireshark opens the frame and displays its data in organized manner. The lower window shows the hex dumb of the frame, from which the UDP message can be seen clearly.

4.5 Docker

Docker is an application that performs virtualization at the operating-system-level. It allows to create multiple isolated user-space instances where applications can be executed. The containers created by the Docker are lightweight and can run the applications in isolation. Being lightweight is only one of the many strengths that Docker brings to development process. Alongside being lightweight it is also portable, meaning that you can build your application locally, deploy it to the cloud and run it from anywhere. [4]

4.6 NT40E3-4-PTP SmartNIC

The Napatech SmartNIC used in the project was NT40E3-4-PTP. It provided full packet capture and analysis of Ethernet Local Area Network (LAN) at a stunning 40 Gbps speed without packet loss.

The SmartNIC provided multiple different key features that made analyzing and capturing of packets effective. It provided a timestamp with 1 nanosecond resolution for every frame that it captured. An Ethernet frame could be received and transmitted every 67 nanoseconds when running at 10 Gbps, and every 6.7 nanoseconds at 100 Gbps. The precision of the timestamp allowed each frame to be uniquely identified. The SmartNIC also provided capabilities to handle fragmented IP frames, efficiently identifying and collecting them before passing them to the same CPU core for processing. [5]

Napatech had implemented many ready macros that made navigating the captured packet easier. These macros moved the pointer to the start of a specific data. They also offered an easy way to slice the data of interest out from the packet.

4.7 Libraries and APIs

4.7.1 Boost

Boost is a portable C++ source library that is free and peer-reviewed. It contains a wide range of different libraries that work well with the C++ Standard Library and provide useful functions and methods that speed up the development of projects. By using Boost, the developers can effectively avoid reinventing the wheel and bugs. Because Boost is maintained by open source community, it can also effectively cut long-term maintenance costs. According to the Boost Background Information on Boost's homepage, ten of the Boost libraries are already included in the C++ Standard Library and more are in the pipeline for standardization [6].

For this project, Boost offered multiple useful libraries, most notably Boost.Asio. Boost also offered an implementation of Smart Pointers that are already part of Standard Library, but for the sake of cohesion the project opted to use Boost's version. Boost.Asio is a cross-platform C++ library that provides developers with a model to handle networking and low-level Input / Output (I/O) programming using modern C++.It is developed and copyrighted by Christopher M. Kohlhoff and distributed under the Boost Software License.

4.7.2 Google Protocol Buffer

Protocol buffers are structured data format that is developed by Google. It works like XML, but is smaller, faster and simpler. Protocol buffers provide an easy way to serialize structured data for read and write operations through different streams. When Protocol buffer is defined and compiled for C and C++, it provides header and cpp files that contain the functions to serialize the data. The code is generated based on the definitions in the proto file. This proto file can be used to reinforce the data structure used between different project and different developers without them needing to know how the other side is handling the data contained in the Protocol buffer.

4.7.3 JSON for Modern C++

JSON for Modern C++ is one of many approaches to create a robust JSON parser for C++. The library is maintained in GitHub, and it has been contributed to by a wide range of people. The design goals listed in README.md states that their aim was to provide an intuitive syntax as well as trivial integration and complete testing of the library. [7]

JavaScript Object Notation (JSON) uses human-readable text to transmit data objects that consist of attribute – value pairs and array data types. It is an open-standard file format and commonly used for asynchronous client – server communications.

```
{
  "pi": 3.141,
  "happy": true,
  "name": "Niels",
  "nothing": null,
  "answer": {
    "everything": 42
  }
}
```

Figure 8. Snippet of JSON format. [7]

The JSON format depicted in Figure 8 can be easily constructed by the functions and constructors provided by the library. User is given multiple ways to initialize the JSON object there are different iterators and methods to access the values in the object.

4.7.4 LibNTAPI

LibNTAPI is part of the 3rd generation driver for Napatech adapters (3GD). The whole driver itself can be divided into four parts: driver, NtService, LibNTAPI and LibNTOS. The driver is the low lever driver that runs in the kernel space. NtService is a daemon that runs in the user space and is the actual driver containing all the adapter specific code. LibNTOS is the OS abstraction library and it handles the OS specific tasks, such as memory mapping, sockets and such.

From the projects perspective the important one is the LibNTAPI. It contains the functions that allow the application to communicate with the NtService daemon.

4.7.5 googletest

Googletest is a testing framework, much like the one offered by Boost. It is developed and maintained by the Testing Technology team at the Google. It is targeted for testing, maintaining and further improving C++ code. [8] Googletest was chosen for the project as it seemed to provide more features and easier syntax at first glance. The basic concepts of writing tests proved to be a simple task as the testing started by writing simple assertions, which test if the condition is true. The results for these tests could be success, nonfatal failure or fatal failure. These assertions were helpful to test the functionalities of the buffers in the project, as well as testing the saving of a filter.

```
TEST_F(TestSetName, TestName)
{
      TestObject obj;
      obj.SetName("Test");
      EXPECT_EQ(obj.GetName(), "Test");
}
```

Listing 1. Example of test using Googletest

The above code snippet demonstrates how to write a simple test using googletest. The test creates the object, tries to set a name for it using the method SetName and then the result is evaluated with EXPECT_EQ macro. The macro's first parameter gets the name field from the object and compares it to the expected value which is the second parameters. If the values match, the test is successful.

4.7.6 spdlog

During the development there was a need to implement some kind of logging to visualize the data that the program was operating on. This logging could have been done by just using something like the following function.

```
void Log(std::string& a_logString) {
     std::cout << a_logString << std::endl;
}
```

Listing 2. Rather simple example of logging function that outputs the string to standard output

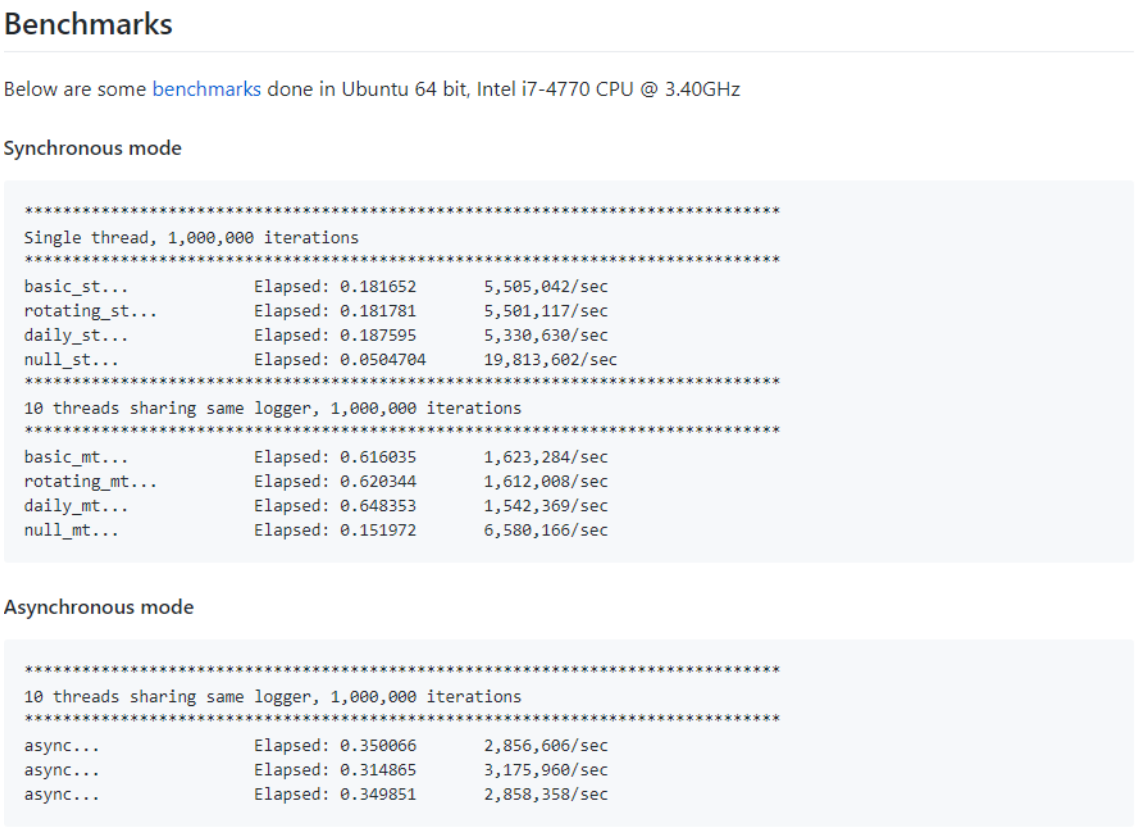
The function described in Listing 2 simply prints out the parameter it is given. This was not convenient as if there was a requirement for different log levels and move complicated inputs for the simple std::string. Logging was achieved by using a C++ library called spdlog. It is a header only library, meaning that it had all the macros, functions and classes visible in the header file forms. This specific library was chosen as the existing server code received for the project included a logging class that used this spdlog library. Spdlog also demonstrated impressive performance as well as nicely formatted prints. The installation process consisted of simple copying over and adding the library to target links.

The existing logging class implemented macros that were used for logging through the project. Below is an example snippet of how the logging was done for standard output.

```
LOG_STDOUT(info, "THIS GOES TO STDOUT");
```

Listing 3. Example how the logging macro was used in the project

The above macro defines the log level as info and writes the text to standard output. Possible log levels were info, warn, error, debug and trace.



Benchmarks

Below are some benchmarks done in Ubuntu 64 bit, Intel i7-4770 CPU @ 3.40GHz

Synchronous mode

```
**************************************************************************
Single thread, 1,000,000 iterations
**************************************************************************
basic_st...             Elapsed: 0.181652       5,505,042/sec
rotating_st...          Elapsed: 0.181781       5,501,117/sec
daily_st...             Elapsed: 0.187595       5,330,630/sec
null_st...              Elapsed: 0.0504704      19,813,602/sec
**************************************************************************
10 threads sharing same logger, 1,000,000 iterations
**************************************************************************
basic_mt...             Elapsed: 0.616035       1,623,284/sec
rotating_mt...          Elapsed: 0.620344       1,612,008/sec
daily_mt...             Elapsed: 0.648353       1,542,369/sec
null_mt...              Elapsed: 0.151972       6,580,166/sec
```

Asynchronous mode

```
**************************************************************************
10 threads sharing same logger, 1,000,000 iterations
**************************************************************************
async...                Elapsed: 0.350066       2,856,606/sec
async...                Elapsed: 0.314865       3,175,960/sec
async...                Elapsed: 0.349851       2,858,358/sec
```

Figure 9. Results of the benchmark.

Figure 9 is from spdlog's GitHub page which also contains a handful of simple examples [9].

4.8 Project classes

The functions and methods that were used to interface with the NapaTech's SmartNIC were wrapped in custom classes that were specific for the project. These wrapper classes made up the backbone of the monitoring part of the project.

4.8.1 Buffers, pools, queues and controllers

DataBuffers (called just Buffers in the early stages of the project) were specific objects for the project which were used to store vital information. They contained the Napatech's captured data in its own format as well as the ID of the stream and connection. These buffers resided in an object pool that was responsible for their lifecycle. Buffers were

requested from the bool as needed and they were marked to be in use. The buffer then stored the data received from the stream and waited for its turn to be sent to the client. When the contents of the buffer had been processed and sent to the client, the buffer's status was updated to indicate that it was available, and it was returned to the pool of available buffers.

The ID of the stream was used to prevent usage of duplicate filters, which could result in certain type of race condition when capturing packets. If two streams tried to capture packets with same filters, only one of the streams got the data. The connection ID was used to identify which client connection the data packet should be sent to.

4.8.2 Writers

A set of primitive writers were defined for the project. DiskWriter was developed as a base class for different type of writers. It handled the creation, opening and closing of a file, as well as writing to a file in the simplest form. The write methods created for DiskWriter handled different data types. From this class the PCAPWriter was derived. This new and refined class handled the generation of PCAP general and record headers, as well as inserting them to the file at the correct moment.

4.8.3 ProtoBuilder

Google's Protocol Buffers generated a large amount of code that handled setting and reading the fields of proto objects, but handling them one at a time was time consuming and repetitive. ProtoBuilder class handles the construction of a proto object with given parameters. The methods take in a reference of existing proto and adjust the fields with given parameters. This way the construction of proto was streamlined and made cleaner.

4.8.4 Streams and containers for them

Stream class wrapped in all the functionality that was required to operate the SmartNIC. The Reference Documentation described five different streams: Info Stream, Event Stream, Configuration Stream, Statistics Stream and Network Stream. From these streams the most important ones from the project's perspective were Configuration

Stream and Network Stream. Network Streams contained the RX Network Stream which was used for the capture and Configuration Stream was used to setup the filters and other configurable features.

The container class for streams kept track of currently active streams and was responsible for shutting them down when the clients so wished. The container also handled the threading of the streams.

4.8.5 Filtering

Creating the filtering for the project was a rather complicated task. The filtering was performed by FilterBuilder, FilterRecorder and FilterManager. FilterManager acted as an entry point from the server to Napa side of the project. FilterRecorder kept track of currently active filters to reduce the wasted resource of duplicate streams as well as eliminate possible data races between two clients. FilterBuilder.

Improving the filter to capture data from certain source or destination address as well as ports required implementing so called Key tests. FilterBuilder's job was to build a proper set of NTPL statements from the parameters and order them in the vector so that the filter can be successfully assigned.

RecordIndex was created to act as a simple data structure that contains all the information related to the filter. It contains information such as source and destination IPs and ports, possible index of existing keys that are used to match said addresses and ports, desired protocol and the stream ID which the filter is assigned to.

4.8.6 Keys

When matching the captured frame against a more specified filter, different tests could be used to achieve this stricter filter. IPMatch test checked the source and destination IP addresses from the received frame against IPMatchList, which contained the desired addresses and if the values match the frame that received frame was captured. According to the Reference Documentation, the KeyMatch test was a more generic version of the IPMatch test.

Key test was the generalization of KeyMatch test and instead of testing different fields in the frame, the test is conducted on a key definition that can constitute of multiple fields from a frame. The captured frame can be tested with multiple Keys. The combination of different keys is achieved with ‘OR’ and ‘AND’ operators. [10]

4.8.7 Configurations and arguments

Testing the connection between the client and the server proved to be a repetitive task after a while, as the client needed to be compiled every time there was a need to switch parameters that would be sent over to the server. To solve this problem the test client was modified to accept parameters as command line arguments. These arguments were parsed using Boost’s program_options library. It offered an easy way to define what type of arguments were accepted and how they would be mapped.

The ArgParser class was responsible for reading the arguments given through the command line and parsing them to vectors. These vectors were then used to construct the Protocol Buffer. As the client was developed only for a test usage and it was not required feature for the project, the ArgParser was rather simple. It did not handle errors well and was quite strict with the format it accepted. For example, defining a protocol was done by passing “--protocol udp”. This set the protocol as UDP but adding anything unnecessary like “--protocol udp tcp” would result in an error, since the class would consider “tcp” to be a command from that string. Each of the configurable value required by the client, could be supplied through the command line. Such values were for example: protocol, source and destination IP addresses, source and destination ports and stream name.

ConfigParser and ConfigFlags were two classes that were created to make the project more flexible. There was a requirement to adjust the size of the pools as well as the address and port of the server, without needing to compile the whole program again. This flexibility was gained by creating ConfigParser, which reads a simple configuration file line by line and picks the set values from there. This parser was rather straightforward, as the configuration parameters needed to be exact in the file.

```
# CONFIGURATION FILE #

[Logging Configuration]
Log_console = true
Log_file = false
```

```
[Buffer Configuration]
poolsize = 1500
buffersize = 1700

[Server Configuration]
Server_address = 0.0.0.0
Server_port = 6666

[Filepath Configuration]
filter_setup_file = FilterMacros.txt
server_log_file = ServerLog.pcap
```

Listing 4. Possible contents of the configuration file

The above snippet depicts how the configuration file would be structured. Separating values to sections was not necessary but it made the file easier to read and manage. The ConfigParser read each line and looked for "=", if it found the correct symbol it then proceeded to split that line to two. These two values were then passed to a different parser function that compared the string from the left side of the symbol to identify the correct configuration parameter. When the correct parameter was found, it was initialized with the value parsed from the right side of the symbol.

When the configuration file was read through and values had been parsed to their corresponding variables in the program, ConfigFlags class would take over.

ConfigFlags was not a class but rather just a namespace that contained the variables with the values from the ConfigParser. The namespace contained functions to set, get and check the values.

5 Architecture

The project consisted of two parts. First part contained the libraries and the API provided by Napatech and was responsible of controlling the SmartNIC to capture the data and forward it to an object pool. The second part contained the implementation of the server, that handled the incoming connections as well as sending and receiving data to client applications. Due to the complexity of creating a proper server from scratch, the thesis focuses more on describing the controlling of SmartNIC and other functionalities related to it. The server implementation was done by modifying existing server code to better fulfill the requirements of the project. A rather simple client application was created to

serve as a debugging tool and to visualize the contents of the Protocol buffers transmitted between the server and the client. Both parts of the project took advantage of object pool design pattern. Reusing the objects obtained from the pool instead of reinitializing them every time resulted in a much faster performance.

A group of utility classes were developed to provide additional support during the development and provide additional value to complete product. These classes provided functions to print easily readable text to console or to a file. As one of the requirements, which came up during the development, was that the final product should be configurable to some degree, a group of parsers were included in the utility group. These parsers were used to parse configuration files that could be used to adjust a handful of values in the program. These utility classes also served as a continuing point for possible further projects, as they were designed to serve universal purpose and work by just plugging them in a project. Further down the line these classes could have been compiled into a single library that would be easily added to multiple projects. To reach this point the classes would have to be developed further so that they could handle a wide range of situation that are encountered in different kind of projects. For this project these classes remained rather simple.

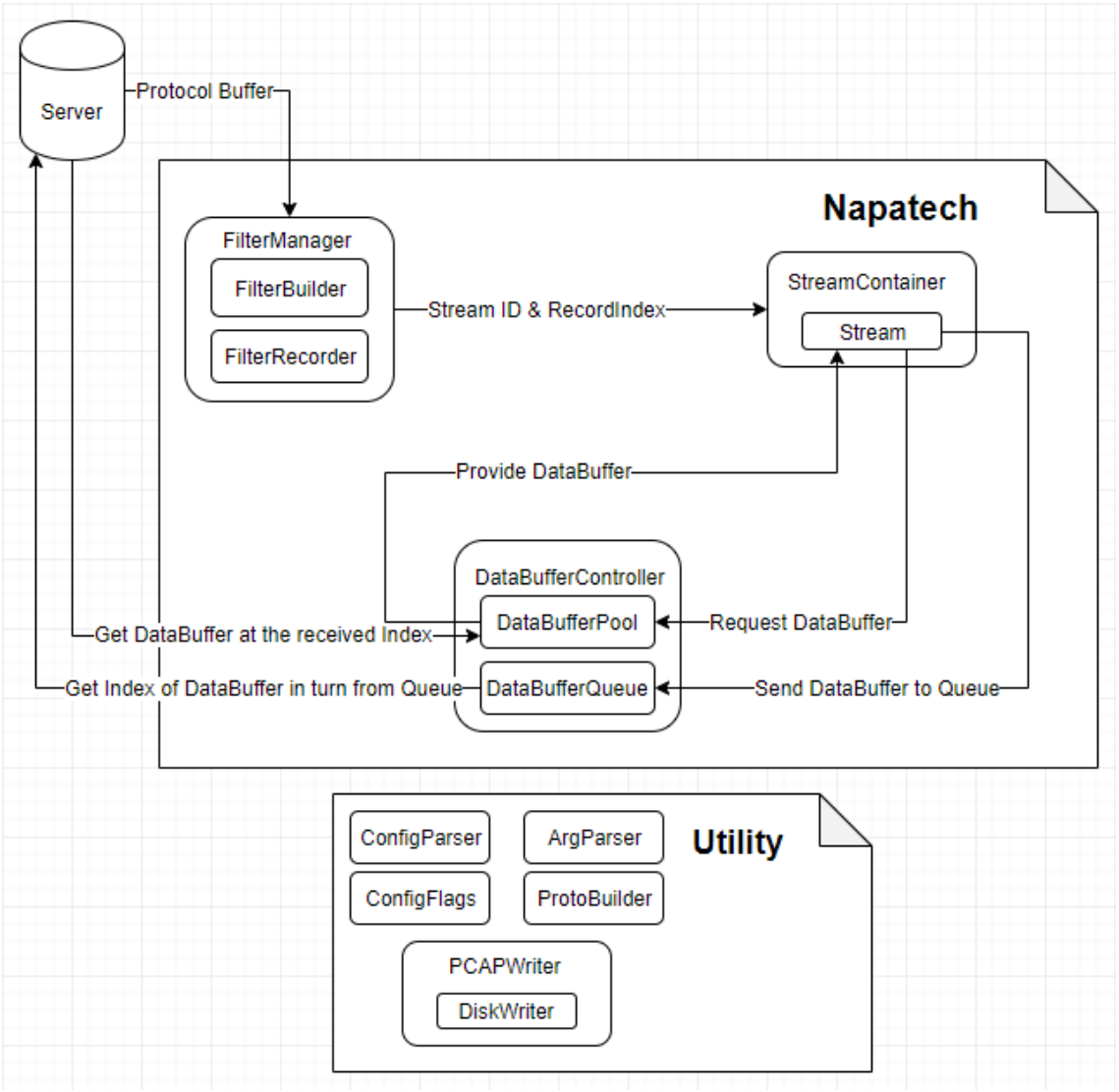


Figure 10. Architecture and data flow in the project as well as how some of the classes were grouped.

Figure 10 describes the architecture and flow of data in the part of the project that handles the Napatech's SmartNIC. The architecture is pictured in its simplest form, without going in too much details how the server part functions. The server was separated from the Napatech as there were no need to tie them together in any special way. The classes displayed in the Utility group serve only to support and are in no way necessary for the execution of the application.

5.1 Object pool

Object pool is a design pattern that offers scalability and performance by allocating a block of memory in form a pool to resources. These resources are commonly user defined objects that are frequently used in the application. The object pool allocates a block of memory in the heap for a collection of said objects. These objects are then requested from the object pool and returned to the calling function if there are resources available. When the requested resource is no longer used, it is returned to its initial state and returned to the pool, from which it can be requested again. The objects stay allocated in the pool until the program is terminated or they are intentionally freed. The benefit of this design pattern lies in the performance boost in situations where initializing an instance of a class is costly.

5.2 Server

The server for the project was created by modifying existing server code. The classes and function contained efficient handling of incoming connections as well as error handling. Data was transferred as a simple stream over the wire. The header was always the same length and the first to be transmitted. The header contained the length of the data frame that followed and other useful information, such as application version number and timestamp. When a client connected, the server started to asynchronously wait for a data to be available in the wire. When data became available the server read alternately headers and packets. Packets were sent to an object pool from where they were then processed. The packets contained the parameters that were used to start the monitoring streams.

Each connection was tagged with a connection ID, to further separate them from each other and to determine which connections each captured data packet were to be sent. While the data transfer was done with header and packet structs, the packets were constructed from Protocol Buffers. This unified the communication on both ends.

6 Implementation

6.1 Creating the server and the client

The project began by sketching out a raw concept of the program parts and how the data should be moved between them. The goal of the project was to separate the data capturing and handling from existing program and turn it in to a service. The requirements for this service were capability to serve data to multiple client connections and capture data without delay. After the initial sketch was completed and some of the features agreed upon, the building of the development environment and the server started.

After studying the examples provided by Napatech and existing server codes, the project began by planning and writing a server that handles a single client connection. The goal was to have a server that could serve to multiple clients, but for the start only a single connection could be used to debug and to get started. Writing proper network code from scratch was tedious and required extensive error handling, but luckily the development could be streamlined a bit by using I/O libraries from Boost. Boost's Asio library provided simple functions to accept incoming connections as well as read and write to sockets asynchronously.

The coding of the server started by following the example of an asynchronous TCP daytime server from Boost's website [11]. The example provided a base for a server and client, that could be expanded upon. When client and server successfully traded simple "Hello world." messages the code was ready to be modified to send more complicated messages. The plan was to have client send parameters to the server, which would use them to start a monitoring session. This was more in line with the requirements of the project. Initially the client and server worked synchronously, but that was only acceptable with a single connection. To be able to handle multiple connections in the future, the read and write operations were changed to asynchronous operations. When running asynchronously, both read and write have a callback function which is called when the required data is available. This cut down the idle waiting and unnecessary blocking. Asynchronous model and callbacks proved to be a handful and caused the messages to get mixed and become corrupted. The problem was solved with proper handling of alternating between reading a header of specified length and reading a packet with length specified in header.

```
void TcpConnection::Receive() {
     boost::asio::async_read(m_socket,
               boost::asio::buffer(m_buffer.data(), HEADER_LEN),
               boost::bind(&TcpConnection::AsyncReadHandler,
                         this,
                         boost::asio::placeholders::error,
                         boost::asio::placeholders::bytes_transferred));
}
```

Listing 5. Asynchronous read function using Boost's ASIO

The function described above reads from the socket to a buffer the number of bytes that is the size of the header. Because the function call is asynchronous, it returns immediately and allows other part of the program to run. The function will continue until the buffer supplied is full or an error occurs. In this case the buffer is exactly the size of the header. When the callback is invoked the buffer contains the header data and can be casted to a struct specifying the header. From this struct the length of the packet can be determined, and the same function implementation can be called with that length.

After the parameters were properly received on the server side, the project moved forward. Next step was the installation of Napatech's SmartNIC in to the server computer, installing the required drivers and applications as well as getting to know the API.

6.2 Installing and getting to know Napatech

The Napatech's SmartNIC was installed to a server computer and required cables were connected. The installation process proved to be a challenge, due to tightly fitted components that were already present in the server. The server was also mapped to a different network which prevented any attempts to remotely connect to it. After thinking it over it was deemed best to move the card to a different server that had the option of remote connection, instead of moving the whole server from the server hall to the office for physical access.

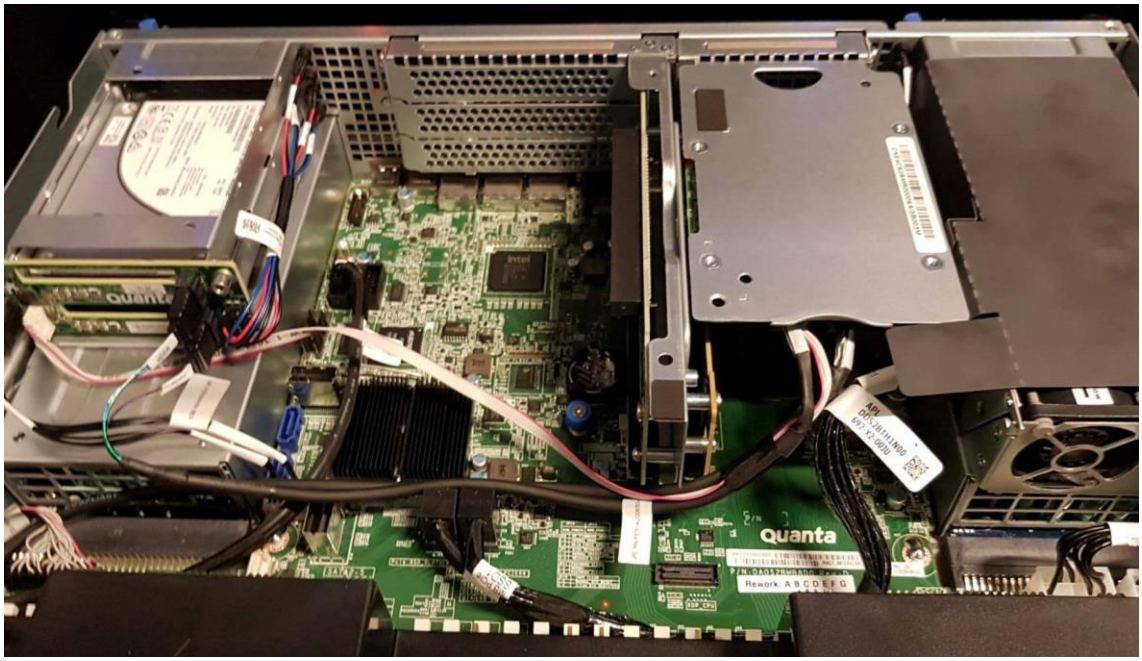


Figure 11. Napatech's SmartNIC in the server

Figure 11 is a picture of the contents of the server machine. Napatech's SmartNIC is on the right side under the metallic cover. When the card was installed it was time to install the operating system, required drivers and download the API. The OS chosen for the project was RHEL 7. When the OS was installed the required updates were configured to be fetched from Nokia's own update repositories. For a first-time user this proved to be a much more complicated task because it involved authentication keys and defining repositories from which to fetch updates.

The installation of the drivers also had problems. When compiling the drivers an error occurred stating that the kernel headers did not match. The error was fixed by removing

and reinstalling the specific version of kernel headers. When the compiling and installation was done the project was ready to move to the next phase, writing a program to capture data with the SmartNIC.

6.3 Starting to write capture software

The first phase in the development of the capture software was to create a program that uses the API to open a stream and capture data specified a simple filter. The data is then written to a file in PCAP format and inspected with Wireshark. This way the validity of the captured data could be verified.

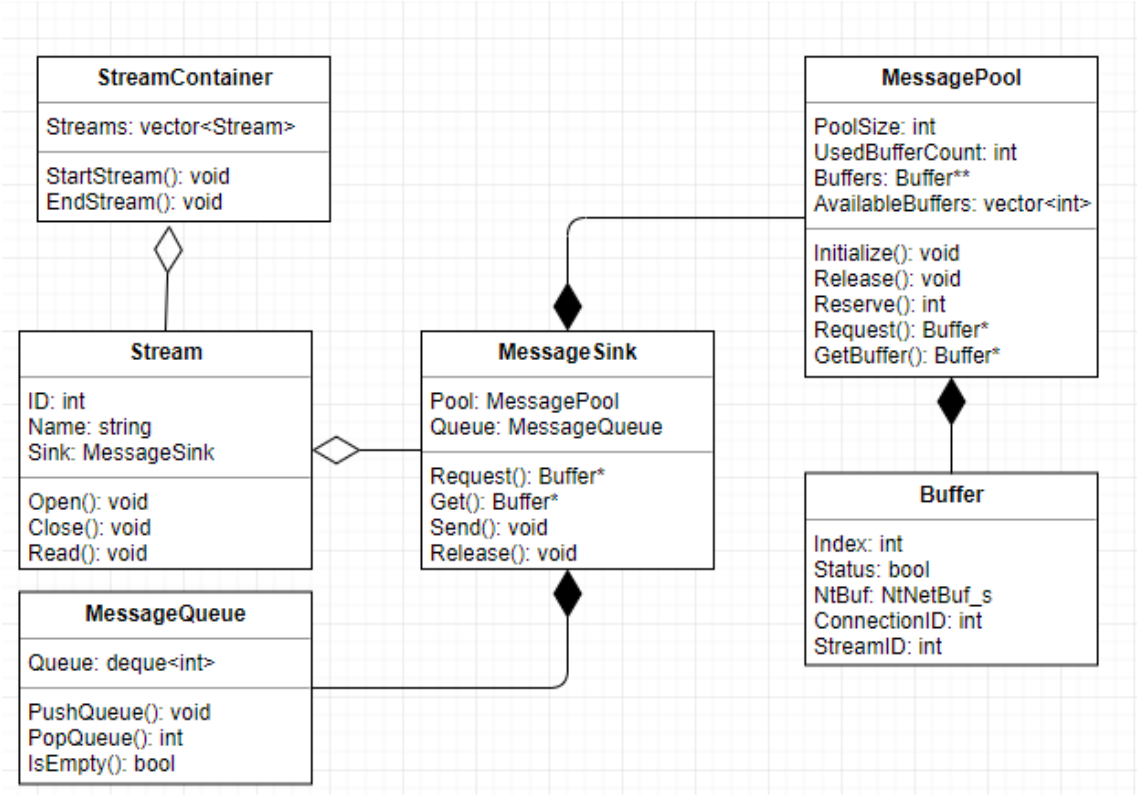


Figure 12. Initial plan for handling captured data

Figure 12 depicts the initial plan that was drafted for handling the data. The captured data is collected in an object pool from which it is then processed in the order dictated by the queue. Figure 12 describes the relation between the classes. Buffers contain the captured data and other important information used in later stages of the program. Pool contains predefined number of ready buffers which are requested and released by the MessageSink class, which acts as a controller that combines the pool and the queue to

a single class. Stream class handles the API calls to Napatech's SmartNIC and is responsible for handling the stream and data capture. StreamContainer is a simple container class that stores multiple instances of the Stream class.

6.4 Implementing primitive filtering

The filtering is done in Napatech's SmartNIC by calling NT_NTPL() function in the API. This is equivalent to running the ntpl script from the command line. NTPL stands for Napatech Programming Language which is used to perform actions on the SmartNIC. The filter is a combination of a filter expression and several different recipes that are functional blocks to further finetune the filter. In its simplest form the filter is assigned to a stream by following code.

```
if ((status = NT_NTPL(configStream, ntplCommandString, &ntplInfo,
     NT_NTPL_PARSER_VALIDATE_NORMAL)) != NT_SUCCESS) {
          /* Handle error here */
}
else {
     /* All is fine */
}
```

Listing 6. Example of using NtAPI to set the filter for the stream

In the above code snippet, the ntplCommandString contains the desired statement which is validated before running it. To assign a simple filter to the stream, the ntplCommandString could be for example as follows: "Assign[StreamId=0]=Layer4Protocol==TCP". This assigns a filter to a stream with ID of 0 that captures all frames where the protocol is TCP.

Writing the filtering is started by using the simplest filter to capture TCP data and writing it to a file. To even be able to inspect the data it needed to be written to a file from which it could be read from with Wireshark. To achieve this a writer class was designed that writes the captured frames to a file and prefixes them with a PCAP header. Napatech offers a way to automatically convert the captured data to PCAP format, but this way the data is kept as original as possible and the conversion is left to the user to implement.

Certain steps were required to get the file in a format so that the Wireshark could understand it to be PCAP and read it. The file had to be prefixed with a global PCAP header which was copied from Wireshark's own wiki pages.

```
typedef struct pcap_hdr_s {
      guint32 magic_number;      /* magic number */
      guint16 version_majos;     /* major version number */
      guint16 version_minor;     /* minor version number */
      gint32 thiszone;           /* GMT to local correction */
      guint32 sigfigs;           /* accuracy of timestamps */
      guint32 snaplen;           /* max length of captured packets, in octets */
      guint32 network;           /* data link type */
} pcap_hdr_t;
```

Listing 7. Required contents of PCAP header

Listing 7 describes the global header which was constructed in the writer class and written to a file upon being opened for the first time. When the file was open, each captured frame that was tagged by the filter was prefixed with a PCAP header and written to a file.

```
typedef struct pcaprec_hdr_s {
      guint32 ts_sec;            /* timestamp seconds */
      guint32 ts_usec;           /* timestamp microseconds */
      guint32 incl_len;          /* number of octets of packet saved in file */
      guint32 orig_len;          /* actual length of packet */
} pcaprec_hdr_t;
```

Listing 8. Struct displaying the format of PCAP record header

Getting the timestamps for the record headers described in Listing 8 were a simple task using the STL function. After a couple of successful captures had been performed, it was time to try to include the IP and port matching to the filter.

6.5 Refining filtering

The program kept throwing strange errors when trying to define Keys and stricter filter. After debugging the program extensively without any luck, Napatech's support provided the answer to the problem. The SmartNIC was running an outdated image of the capture software and needed to be updated. This was an easy task since the drivers and software installed contained a program that was used to change the image. It turned out that there were two different memories that could contain different images and acted as a

backup. If one of the images became corrupted during the update, the backup image could be used to still perform actions on the card.

After the image was updated the stricter filter did no throw any errors. The captured packets were written in proper format to the PCAP file and there were not any Malformed Packets. This form of filtering was satisfactory, and the project moved forward to further redefine the server side as well as the Napa side of the project.

The new filtering developed at this phase of the project used Dynamic Descriptors that offered predefined offset to the beginning of different layers.

6.6 Tackling the threads

To be able to serve multiple clients simultaneously the server needed to be ran in asynchronous mode. The server was threaded to have a couple of threads for sending and receiving. Threading in Boost was initially a hard concept to grasp, as it revolved around the boost::asio::io_service. After initial struggle trying to learn to use the io_service, it became clearer how it functions. The boost::asio::io_serivice can be thought as a queue that guarantees that operations will run only in threads that called the io_service's run() method.

After the server was threaded somehow and the messages were being sent and received asynchronously it was time to rethink the filtering. It was obvious that there was bookkeeping required from the filters so that multiple clients would not try to open streams with the same filter conditions. First draft of a FilterManager was created. The primitive FilterManager is a class that contains all the received source and destination IPs as vectors within vectors. When a new client connected the IPs were checked against the existing IP vectors and it was then determined if there was an existing filter for these IPs. If a filter existed the index of the Key set was returned, which was used in the Assign statement for the stream. This prevented the program from trying to define a duplicate Key, which would have resulted in an error message during the NTPL call.

6.7 Sending captured data to client

So far, the project had been debugged only by writing PCAP files in the server side and inspecting them for Malformed Packets or other indications of bugs. When the FilterManager seemed to work well enough and opening two streams with same filter conditions did not result in errors, it was time for the project to take the next step. The data could not be sent to client in the Napatech's own format. It had to be processed and parsed somehow to extract the requested data and then send it to the client. This way the client would not need to know anything about the Napatech's API and could just focus on handling the raw received data.

The captured data form the SmartNIC is basically just an array of data. Extracting the correct layer from the data could be achieved by moving the pointer forward by correct amount. Luckily the API provided an easy way to adjust the offset of the pointer by using Dynamic Descriptors. These descriptors were used to move the pointer to the start of a specific layer. Dynamic Descriptor 2 was selected for the project, as it provided default offsets to Layer 3 and 4 right away. This type of descriptor also offered a way to determine the length of the captured data. That length was then used to write the correct amount of data to client. At this point the data was written to client as it was, a plain stream of bytes without any communication of success.

The validity of transmitted data was verified by inspecting the length of data being transferred. When the server and client reported matching number of bytes being transferred the PCAPWriter was plugged in and the data was written to PCAP file in the client application. The data that should be captured and the client should receive was narrowed down to be a simple UDP data, that was generated by a simple bash script.

```
#!/usr/bin/env bash

echo "Sending UDP messages to ip address $1 and port $2"
echo -n "Hello" >/dev/udp/$1/$2
echo -n "This is dog" >/dev/udp/$1/$2
echo -n "Now one empty message after this one" >/dev/udp/$1/$2
echo -n "" >/dev/udp/$1/$2
echo -n "Empty message sent and prolly doesnt show in wireshark" >/dev/udp/$1/$2
```

Figure 13. Simple bash script that sends UDP to specific IP and port.

The simple script pictured in Figure 13 takes an IP address and a port as parameters and echoed a set of messages to them. This data was then captured by the SmartNIC and sent to client, where it was written to PCAP file. When the file was opened with Wireshark it displayed the sent messages in the same manner as displayed in Figure 7 in paragraph 4.4.

6.8 Sending Protocol Buffers

After the data transferred between the client and the server was verified to be identical, it was time to start considering a proper implementation of communication between the two. Google's Protocol Buffers were chosen for the task as they provided a flexible way to define a type of capsule that could contain all the data.

The Protocol Buffer (from now on referenced as proto) contained multiple fields, such as acknowledgement message, general header containing timestamp and other important information, requests to start and stop monitoring, and maybe the most important of them all, the payload.

The payload was defined as "oneof" which indicated that there would be only one of the fields from the payload field at a time, in the proto. The payload field contains one of four different fields that are vital in the communication in the project.

The possible fields are a response to a monitoring request, request to start a monitoring session, a request to stop a monitoring session and a field that contains the monitoring data. Response to monitoring request contains the monitoring session ID for the client. This ID is used on the server side to differentiate the streams and which client is subscribed to which stream. Request to start the monitoring session contains a set of parameters that are used to build the filter for the monitoring. Stop request contains only the monitoring session ID and the data field contain the monitoring data captured by the SmartNIC and the session ID from which it was captured.

Google's Protocol Buffers offered generated methods to handle the data fields in them. These methods were used to set and read the fields from the buffers. Setting them one

at a time proved to be a tedious task, so a helper class ProtoBuilder was used to construct protos. Sending the proto between the client and the server was done by serializing it to bytes and then sending it over the wire. On the other side the bytes stream was serialized back to a proto object and the values for starting a monitoring session were successfully read. The project moved forward to modify the filtering to use these values.

6.9 Protocol Buffers in filtering

Initially the filtering was done by reading the values from the Protocol Buffer and running them through a complicated set of functions that checked for duplicates and such, but it proved to be too much to handle in a single class. RecordIndex was written as a simple solution to have an object whose sole purpose was to store the required information related to a specific filter setup. Initially it also contained the Keys used to set up the filtering, but further down the line it proved to be redundant and was removed. When the client sent the Protocol Buffer over to the server, it went through a FilterRecorder class, which determined if the given parameters were used to initialize a default stream (simple UDP, TCP or SCTP without a set of IPs or ports) or a more complicated filter. This FilterRecorder also stored a vector of these RecordIndexes to keep track of existing filters. By far this was the most complicated feature to implement, as the monitoring streams could be “tapped into” but not opened multiple times. If multiple clients were to request the same monitoring data, instead of opening a new stream and defining the filter again, the duplicate clients would just open a stream with existing stream ID and access that same stream of data.

6.10 Simplify test client

End-to-end testing with the simple client was a tedious task as changing the parameters it supplied to the server required recompiling it every time. This issue was tackled by implementing the ArgParser described in section 4.7.7. This parser simplified and sped up the testing. When the end-to-end tests were completed successfully on the test client, it was time to try to get the connection from the existing software. Connecting from the existing software to the server was out of scope for this project, as the goal of the project was to create a server containing the monitoring capabilities of that existing software.

6.11 Adding flexibility to the server

The server side of the project had the same issue as the test client: it required recompiling every time parameters needed to be changed. To make the server more flexible, ConfigParser and ConfigFlags were developed. These classes were described in section 4.7.7 alongside the ArgParser. By using the functions from the ConfigFlags the user was able to specify what type of logging would be enabled during run time and much more. The configurations displayed paragraph 4.7.7 was easily expandable in case the project required more options in the future. As the ConfigParser had moved away from the use of JSON format, the JSON library introduced in paragraph 4.6.3 became redundant.

7 Results

The project appeared to work as expected when tested with the self-made test client. Connection with the intended target application was partially tested and the transfer of Protocol Buffers seemed to work as required. Minor issues were encountered with the stability of the server part of the project. Invalid handling of the buffers invalidated the pool and resulted in segmentation faults. This was soon fixed by correcting the returning values of function in the classes that handled the buffers.

Towards the end there could have been room for some optimization of the code and classes, but the project was running out of time. Even though the project functioned and performed the tasks it was given, it did not properly capitalize on the benefits offered by the latest versions of C++.

From a learning point of view the project was a success, as it allowed to peer straight into the heart of networking and how the data travels in there. It taught a great deal of how to interface two applications developed by two different people, as well as how to create and maintain a CMake project.

When the server and the application did not encounter any errors during the test runs, it was set up to start as a service so that it would be constantly running even if it crashed. This was a temporary solution as the initial plan was to have the application running in a Docker container.

8 Conclusions and further development

For further development the project could explore the possibilities of refining the way the configuration is done. A simple CLI dialog would be enough as it moves away from needing to know the layout and possible parameters of the configuration file. The scalability is not an issue as the SmartNIC is more than capable to crunch through a ton of traffic. The macros provided by Napatech also have a wide range of features that can be implemented, such as further identifying the type of TCP traffic and using more complex filters that utilize hashing. Additionally, the project could be expanded to handle fragmented frames during transfers and captures.

Utilizing the SmartNIC instead of a normal NIC provides remarkable performance boost to the system. When implementing some type of network monitoring, it does not have to be confined to a single existing solution but instead it can be a combination of many. As the technology evolves and transfer speeds keep rising, monitoring becomes increasingly complicated and specific type of hardware need to be developed to achieve the optimal monitoring solution.

The project described in this thesis was just one type of manifestation of a monitoring solution. The API provided by Napatech did most of the heavy lifting and left handling of the data to the user. Without reference to other SmartNICs from different manufacturers, the cards used in this project are more than capable of handling such a monitoring task.

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