

TCP PEP

TCP Performance Enhancing Proxy to Support
Non-interactive Applications

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Chapter 1

Intro

Chapter 2

Background

In this chapter we will present some of the required background knowledge to understand the concepts presented in this paper. Focusing on topics that are outside the common understanding of network programming, especially details of certain congestion controllers and network protocols will be discussed. The rest of the thesis will assume the following topics are known to the reader.

2.1 TCP/IP

Perhaps the most well known internet transport protocol is the Transmission Control Protocol (TCP). It is known for providing reliable and in-order delivery of packets using acknowledgments and re-transmissions [6]. It was first introduced in 1974, but is still the most used internet protocol. However, as the demands of the internet have changed, TCP has not. Though TCP has been updated with minor extensions over the years, such as increased initial windows or new options, the core ideas have stayed the same [2].

Concepts as the end-to-end argument still play a vital role in how TCP is used in the modern internet. TCP is suffering under the illusion that all logic should be placed on the endpoints as the end to end argument denotes. Even if it spans multiple different domains with varying topologies and demands, especially between wired and wireless domains.

- **Wireless Domain:** A wireless communication domain refers to the transmission of data over a wireless medium without the use of physical connections such as wires or cables between devices. This domain covers a variety of technologies, including 3G, 4G, and 5G for mobile communication, Bluetooth and Wi-Fi for close-range communication, and satellite communication for worldwide communication.
- **Wired Domain:** Unlike a wireless domain, a wired domain provides a

steady and reliable bandwidth with low error rates and high throughput. The use of Ethernet and Fiber are typical for wired networks, they enable the transmission of large amount of data over long distances and low signal noise.

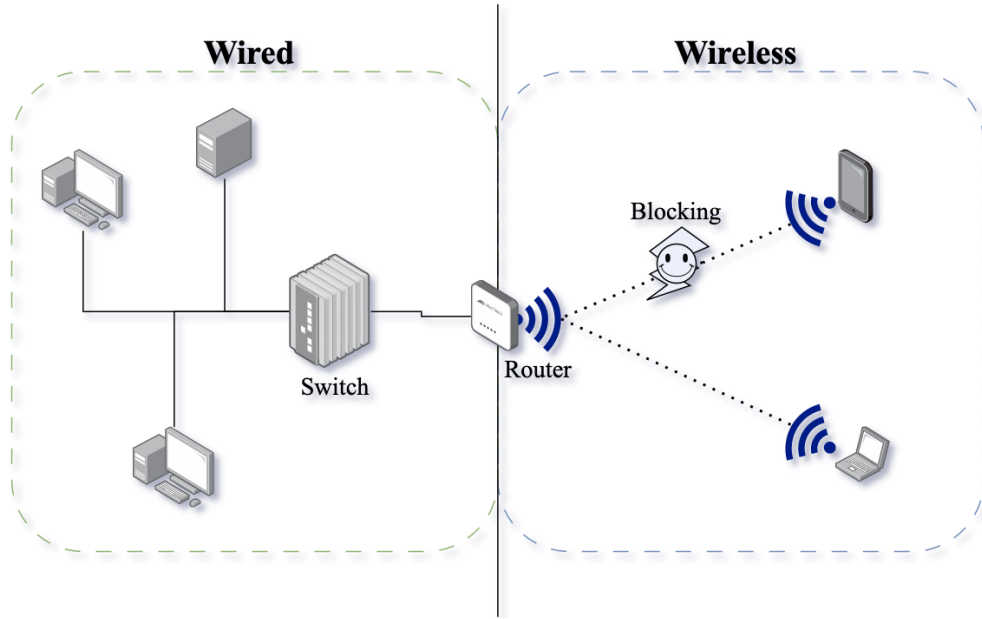


Figure 2.1: Example of network domains

Each domain has different requirements that a single TCP connection cannot provide. Fig. 2.1 shows the two domains and their characteristic differences. Usually, wireless domains experience a lot of changes in connectivity and bandwidths, while the wired domain usually is considered stable. This creates problems for the "modern" TCP which, because of the end to end argument, normally spans multiple domains. Especially congestion control has problems adapting to high fluctuating bandwidth across long distances and multiple domains.

2.1.1 Congestion Control

Congestion occurs in the internet when a network's resources, such as routers, are overloaded to the point that they diminish quality of the network [16]. Packet loss and high delays are common issues associated to high congestion in the network. To solve the problem of congestion, a distributed algorithm is used: Congestion Control. The main goal of congestion control is to maintain a stable network, while still utilizing the available bandwidth shared among all flows. This is achieved by additively increasing the sending rate, and multiplicatively reducing the sending rate when detecting congestion [15].

Congestion can be detected by packet loss, changes in delay, but also by explicit notifications.

Over time different variations of congestion controller have emerged. Although their goal is the same, reduce congestion in the network, their approaches vary.

- **TCP Reno:** Reno embodies the traditional approach to congestion control. Slowly increasing the sending rate while the network is stable and drastically reducing it on packet loss. TCP Reno was designed for unstable and dynamic networks, where the rapid response rate is crucial to prevent network overloading. However, the slow start rate and aggressive reduction of the sending rate make it sub optimal for more stable networks, where packet loss is less frequent and predictable. Consequently, TCP Reno's reliance on packet loss may lead to unnecessary rate reductions and decreased network throughput.
- **New Vegas:** New Vegas is similar to TCP Reno in most aspects, the main difference is the use of delay to detect congestion instead of packet loss. This makes New Vegas able to react faster to congestion, however it also introduces some interesting side effects. If New Vegas competes with TCP Reno flows, it will start reducing its sender rate before TCP Reno does, this leads to New Vegas losing out on possible bandwidth.
- **Cubic:** Cubic improves on the idea of TCP Reno by using a cubic function to adjust its (congestion window) sending rate in order to achieve higher throughput in a fast manner. Cubic is very efficient in highspeed networks and known for handling large data transfer over long distances. However, Cubic is not as reliable and robust as more traditional congestion controllers like TCP Reno.

In summary, the main differences between TCP Reno, New Vegas and Cubic are their approach to congestion control, their performance in different types of networks, and their trade-off between efficiency and reliability.

2.1.2 3 Way handshake (0 RTT)

For TCP to establish a connection it uses a three-way handshake. Initially, it transmits a synchronization (SYN) packet to the desired endpoint. The endpoint responds with an acknowledgement and a synchronization packet of its own (SYN/ACK). Finally, the client responds with a acknowledgment (ACK). At this point both endpoints have confirmed that they are ready for further communication. For any connection to be established this handshake has to be done. For short flows that terminate in just a few round trips

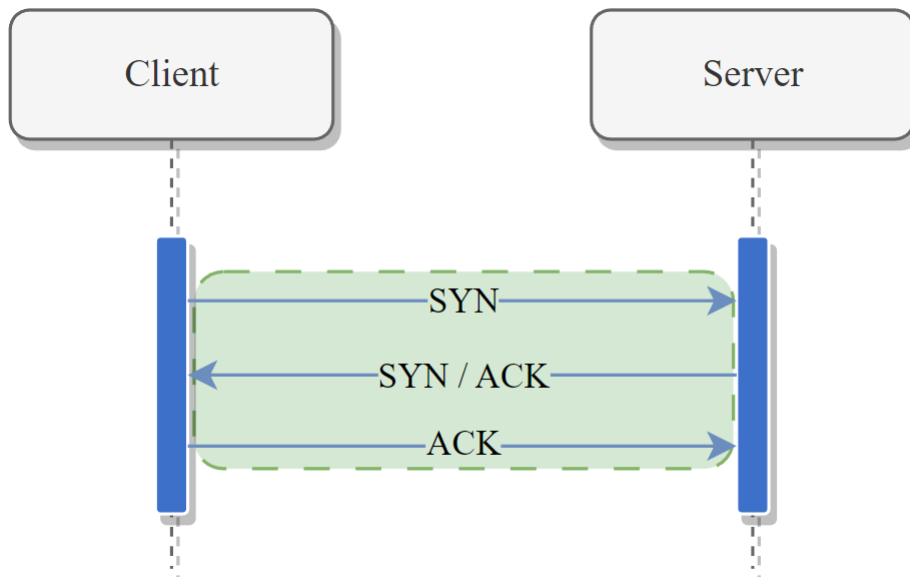


Figure 2.2: The TCP handshake procedure

the initial TCP handshake can be a bottleneck, which is made worse if the connection is using a proxy and has to exchange additional information.

2.1.3 TCP Options and Fast Open

A TCP connection can be configured with optional header extensions called TCP Options [3]. These options change the default behaviour of TCP or add new features. One such feature is TCP Fast Open, which allows data to be added to the initial synchronization packet. A typical use case could be adding a HTTP GET request, thereby saving an entire round trip. In general flows that terminate in a few round trips greatly benefit from this feature. The reason being, the bottleneck in such connections often lies within the initial TCP handshake. Therefore, by removing the extra round trip required to send the first data packet, a significant amount of time can be saved.

TCP Fast Open also has other benefits, such as establishing connections to proxies [2]. When you are trying to establish a connection through a proxy, you get the added delay of a second round trip sending the desired endpoint. This can be avoided by using TCP Fast Open to send the desired endpoint in the first synchronization packet to the proxy. "SYN forwarding" enables the users to establish a proxy connection without any added delays, however it does depend on the user's application to use TCP Fast Open.

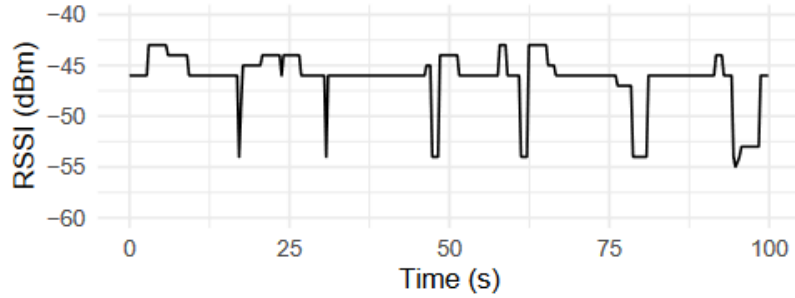


Figure 2.3: 5G bandwidth fluctuations from humans

2.2 Future of wireless communication.

The future of wireless communication has seen a lot of improvements such as highly increased bandwidth achieved through advanced technologies like 5G and beyond. Millimetre frequency bands have opened up new possibilities for wireless communication. These higher frequency bands offer greater capacity and can accommodate more devices, however high frequencies come with a set of new challenges such as highly fluctuating bandwidths. This fluctuation can be influenced by various factors such as signal interference, obstacles in the signal path, and environmental conditions.

2.2.1 5G Millimetre Wave

The emergence of 5G Millimeter wave communications has opened the doors for low latency networks with multiple gigabit bandwidth. This is achieved by using higher millimetre wave (mmWave) frequencies in the range of 30GHz to 300GHz, which has a lot of benefits [1]. A wider spectrum of frequencies to choose from and higher data transfer rates are just some of the many benefits mmWave provides. But along side the benefits, mmWave has also introduced a lot of new challenges.

A big problem with millimetre wave communication is signal path blocking also called "Line of sight blocking" [13]. It's caused by the use of Beam-forming to increase the bandwidth and range of millimeter wave signals. Beam-forming focuses the signal in a certain direction making any blocking of the signal path devastating for the bandwidth. Even the human body can create enough blockage to drastically reduce the bandwidth. This causes huge fluctuations in the bandwidth whenever the signal is blocked.

Fluctuating bandwidths lead to unstable TCP connections with a worst case of losing packets. Current TCP congestion controllers such as CUBIC, New Reno or New Vegas struggle when reacting to sudden fluctuating

changes. They are simply not able to utilize the high bandwidth when it is available. Simply increasing the aggressiveness of a congestion controller is not an option either as it would disrupt the internet and not be TCP-friendly. A possible solution could be to buffer packets at the 5G base stations, having the data ready for when the bandwidth is high. This however creates a new problem, bufferbloat.

2.2.2 Buffering

Buffer bloat

The buffer bloat problem occurs when the systems between the endpoints buffer so many packets that the latency drastically increases and the reliability of the network as a whole goes down. The increased latency is detrimental for interactive (latency sensitive) applications. Generally it's preferred to drop packets and keep buffers small to avoid buffering time sensitive packets such as synchronization packets. Although this works in most cases, it's far from an optimal solution.

The increased bandwidth and low latency promises of new technology such as 5G has put a lot of pressure on the efficient forwarding of packets. Small buffers are therefore the standard, But at the same time, fluctuating bandwidth has shown the potential need to buffer packets for non-interactive traffic. Most focus has been on accommodating for latency sensitive applications like virtual reality or remote surgery to name a few.

This thesis will explore non-interactive applications where latency is not that critical and more buffering is acceptable and most likely desirable. By splitting traffic into interactive and non-interactive we can improve the performance of both. By having very small buffers for interactive applications we avoid bufferbloat problems, while utilizing the benefits of big buffers for non-interactive applications.

Packet Scheduling

A method of reducing the effects of bufferbloat is packet scheduling. A system should not send more packets than the weakest link can handle, this idea is built into TCP in the form of congestion control. However, when buffers grow to the point of causing bufferbloat, TCP's congestion control algorithms are unable to confidently determine a sending rate. Packet scheduling can solve this problem as it usually controls the size of the buffers. It makes sure queues can grow when needed, but keep the overall state of the buffers low. Packet scheduling has a lot more to offer than simple queue management,

this will be explored later.

Proposed packet scheduling algorithms:

- **FQ CoDel:** The Flow Queue Controlled Delay algorithm, FQ CoDel for short, was partly developed to deal with the bufferbloat problem. Its main goal is to reduce the impact of head-of-line blocking and give a fair share of bandwidth by mixing packets from multiple flows [9]. Internally FQ CoDel uses a FIFO queue, classifying packets into different flows to provide a fair share of bandwidth.
- **HTB:** Hierarchical Token Bucket is a queuing discipline based on assigning different classes a certain amount of bandwidth and sending rate. Because of its extensive bandwidth and delay management it's a good option for testing, especially in a virtual environment.

2.2.3 Non-Interactive Applications

Non-Interactive applications such as web traffic, file transfers and video streaming can benefit from larger buffering, especially with fluctuating bandwidths. This is because if we are able to buffer the packets closer to their final destination, we have them ready to be sent when the bandwidth changes. By buffering them we can decrease delay times and achieve faster total completion times for non-interactive traffic.(need citation or prove it myself?). At the same time, interactive applications will not suffer under large queue delays that occur under normal buffering.

2.3 Proxy

Proxy servers play a big role in the modern internet, delivering benefits such as anonymity and increased performance [14]. A common use case for a proxy is caching by keeping a copy of popular resources such as a websites. This reduces the latency of accessing the resource as long as the proxy is closer to the user than the original copy. Locality plays an important role in the total latency as any transmission will always be limited by the speed of light.

A proxy can also be used for privacy similar to a Virtual Private Network (VPN). By redirecting network traffic through a proxy, the origin of the traffic appears to be the proxy server rather than the actual end-user. Hypertext Transfer Protocol (HTTP), a popular internet protocol used for accessing websites, has this functionality built in using HTTP tunnels and a special CONNECT method in its header.

```
CONNECT mn.uio.no/:22 HTTP/1.1
```

2.3.1 PEP

A performance enhancing proxy (PEP) is a connection splitting proxy designed to increase performance of applications using it. The idea behind the PEP is putting more logic such as connection management, buffering, caching inside the network. As the name suggests, a PEP is designed to enhance the performance, but can also introduce new features to a network. An example of a new feature is the multipath support the TCP Transport converter gives. [2].

2.3.2 PEP for wireless communication

Performance enhancing proxies are already deployed and in use for a lot of wireless communication, especially satellites and radio access networks [12]. They have an inherent performance increase just by splitting the connection between the wireless and wired domains. These PEP's are therefore often installed at the base stations. However they are unable to distinguish between interactive or non-interactive traffic, meaning their buffers need to be low and still suffer from fluctuating bandwidth problems.

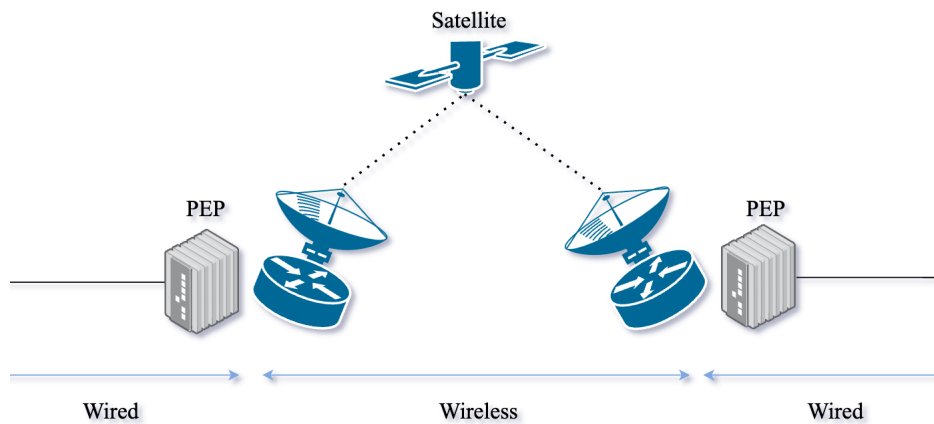


Figure 2.4: PEP installed to support Wireless traffic over satellite.

2.3.3 Transparent vs Non-Transparent

A big discussion regarding PEPs has been if they should be transparent or non-transparent. Transparent PEPs are not visible to the applications that use it. They silently split the connections and spoof the IP-address of both the client and server [4]. This is prone to cause unintended side

effects, such as certain TCP options not being forwarded and security concerns. Non-Transparent PEPs on the other hand are explicitly chosen by either the client or the server, and the sender is aware of the proxy splitting the original connection. This approach can be seen as more ethical and potentially remove some of the stigma associated with PEPs, this however requires modifications at the sender side utilize the PEP.

2.4 Linux

Linux is the most famous open source kernel freely available for anyone to use and modify. Because of the open source nature of Linux, there have been many various operating system implementation based on the Linux kernel. Ubuntu, Fedora or Manjaro are just some of the most famous Linux based operating systems out there. For developers, Linux is the perfect platform to experiment and test their new innovations. You are able to modify and recompile the kernel itself on the fly, and then test the solution on a live operating system. Linux supports most standards and is used by most major corporations such as Facebook, Amazon, Netflix and Google.

2.4.1 Kernel Modules

Thing that makes Linux truly extensible are Loadable Kernel Modules (LKM). Kernel modules are programs that can be loaded at runtime into the kernel and run with kernel privileges. Running with kernel privileges has a lot of benefits such as having access to internal structures and kernel symbols. Most drivers in the Linux kernel are written as kernel modules as they need access to the system internals.

Congestion controllers and packet schedulers are also usually implemented as kernel modules. That is because Linux exposes a struct with function pointers that can be overwritten by a module. Making the kernel call the new functions instead. Because kernel modules run as part of the kernel they do not need to use system call to do basic I/O as using sockets. Removing the overhead of system calls makes the kernel modules run much faster than default user space programs.

However, the using Linux kernel modules has the drawback that the program is bound to Linux. The modules will only work in the context of the Linux kernel as they depend on the internal functions, and that they are part of the kernel. Most other operating systems like MacOS will not allow user defined modules to run with kernel privileges. Additionally, any bugs or error in the kernel module will make the entire kernel panic, which usually requires a complete system restart to fix.

Chapter 3

Design

A good design for the PEP is crucial as it both needs to be robust, fast and reliable. Not all of the goals are equally achievable, and other aspects need to be considered such as cross platform compatibility. The overarching goal is to improve the completion times of the non-interactive traffic while avoiding to disturb the interactive flows.

The second key design aspect focuses on 5G. A goal of the PEP is to better utilize the fluctuating bandwidth, this will influence many aspects such as the placement strategy. This contributes to the overarching goal of making the best use of the new 5G technology.

In this chapter we will explore the different ways of achieving our goals and compare them to each other.

3.1 Justification for designing a PEP

The ossification of networks, particularly TCP, has been a longstanding issue. [8]¹ Over the years, the internet has evolved, but the core protocols, like TCP, have remained relatively unchanged. This leads to challenges when attempting to introduce extensions or modifications. Especially, altering such a fundamental protocol could disrupt countless systems and applications. Which leaves us to explore new ideas using middle boxes. A PEP is such a middle box, it can enhance the performance without changing TCP itself.

Using a PEP in combination with 5G has additional benefits. Default TCP with 5G needs to cover both the stable network and the fluctuating wireless domain. However, with a PEP we are able to split the domains and perform optimizations, such as congestion control, tailored to each specific domain. Achieving the same optimization by modifying TCP would be a

¹Cite this

endless close to impossible with the tight integration of end to end congestion control.

²

The development of PEPs have seen a lot of resistance over the years because of the end-to-end argument: keeping logic at the endpoints.

3.2 PEP Programming

3.2.1 Choosing the Programming Language

A PEP aims to boost the performance of applications that use it. The speed at which they can process and forward packets is critical. Especially when wanting to utilize the rapidly fluctuating bandwidth of 5G, we need to react as fast as possible. Therefore, the programming language chosen for a PEP has a direct impact on its efficiency. Interpreted languages like Python might not offer the speed necessary for high-performance tasks. Even Java, while running within the JVM, can potentially introduce delays. The languages best suited for high performance are C, C++ and Rust. Both C and C++ are very similar and well suited for high performance systems, Rust has an additional aspect as it supports compile-time checking for race conditions.

The C Programming Language C has been the optimal language for high performance systems since its creation in 1972. [10] It was originally created for UNIX when it needed a higher level language, and now is the main programming language behind most operating systems such as Linux, Mac and Windows. Being very close to its predecessor, assembly, and compiled to a binary, makes it one of the fastest languages we have to date. Heap memory management is explicitly done by the programming with no support for garbage collection. The unsafe memory management is one of the main challenges when programming in C, which however can be a benefit because a runtime garbage collection usually results in performance loss.

Listing 3.2.1: Default C program.

```
1 #include <stdio.h>
2
3 int main(void)
4 {
5     printf("Hello World!");
6     return 0;
7 }
```

²PEPs with 5G, different "domains" works better than normal PEPs

3.2.2 Kernel Module Vs. Userspace Application

A major design decision is whether to write the PEP as a user-space program or a kernel module. This will also influence the choice of programming languages, because kernel modules mainly are written in C, although Rust has now also been slowly adopted.³ Making system calls (syscalls) can introduce some performance overhead, which is a consideration when looking at user-space programs. In contrast, MacOS offers the kernel extension framework for tasks that require deep system integration, though it comes with its own set of challenges and constraints.

Opting for a user-space application has the advantage of being cross-platform, meaning it can run on multiple operating systems without major modifications. On the other hand, a Linux kernel module runs within the kernel space, eliminating the need for syscalls and often offering better performance. However, it's tightly bound to the Linux environment, which might limit its applicability in diverse systems.

3.2.3 Optimal Choices for PEP Performance

Because of the efficiency and possibility of kernel modules, C offers the optimal performance for a PEP. This combination leverages C's high-speed capabilities and the direct kernel integration, minimizing overheads and maximizing efficiency. This choice binds us to the Linux kernel, but this is a small price to pay for salvation.⁴

3.3 PEP Transparency

Transparent and Non-Transparent PEPs differ in their visibility and interaction with applications. The choice between these two options all have their own set of advantages and challenges. These include ethical concerns regarding transparency, potential issues associated with unaware applications, and considerations for deployment.

3.3.1 Transparent

Transparent PEPs offer an advantage in deployment as they can be introduced without any changes on the client or server end. This ensures that even legacy applications can benefit from the PEP. Also, by nature, the PEP will always be on path of the original connection. However, when unknown middle boxes interfere with a connection, unintended side effects, such as

³fill inn more

⁴Find a actually good way to say this. :) Also! Future work could be comparing to a userspace application?

losing TCP Options, become more likely. Furthermore, without knowledge of the PEP, applications cannot modify their behavior, which limits their extensibility.⁵

3.3.2 Non-Transparent

Since applications are fully aware of the PEP when it is non-transparent, we can adjust the PEPs functionality based on the application using it. Applications can also adapt their behavior, optimizing their operations based on the presence of the PEP, leading to potential performance improvements. Although side effect may still occur, applications are aware of them and can actively mitigate them. Deployment, however, becomes more problematic as for the PEP to be efficient it needs to be on the shortest path which is no longer guaranteed.

3.3.3 Choosing a Non-Transparent PEP

Although transparent PEPs are more common, the goals the TCP PEP aligns more with an non-transparent PEP. The possibilities and potential a non-transparent PEP has is worth breaking the standards.⁶ Since the goal is to increase the efficiency of a certain kind of application, non-interactive, it will be important that the PEP can adapt.

3.4 Connection Handling in PEP

The way the PEP manages connections primarily determines its functionality.[7]⁷

3.4.1 Connection Splitting

A performance enhancing proxy does not inherently need to be connection splitting. Depending on its implementation within the network stack, a PEP can buffer and process packets without requiring the termination of the end-to-end connection. A PEP could passively monitor or manipulate the traffic, or or even preemptively transmit ACKs.⁸

There are multiple benefits and disadvantages with using a connection splitting PEP. Firstly, a connection splitting proxy can additionally split the connection into different domains. As discussed in Chapter 2, the internet consist of different domains with their own characteristics. Being able to split the connection into their different domains, enables the PEP to select

⁵Talk more about ethical concerns?

⁶This entire sub section should be rewritten, but point stands

⁷Use this citation for when discussing what type of pep (layer)

⁸Picture of a PEP only sending ACKs

an appropriate congestion controllers based on the technology and topology of each domain.

The connection process to the PEP, and later on the endpoint, is established by informing the PEP of the desired endpoint of the client. This can be achieved by a variety of ways where the goal is to attach additional information to the default connection process of TCP. Preferably, we do not want the overhead of needing an entire additional round trip just to pass this information. Additionally, the client needs to select the PEP, without altering the default socket connection scheme. There are a few different ways of achieving this, which will be discussed below.

3.4.2 PEP Selection

The next challenge is how does a client choose a PEP. We do not want to change the normal socket based scheme of creating a connection, as old applications would need to rewrite a lot of their code. An important prerequisite for the PEP to work is that the PEP is on the shortest path to the chosen endpoint. This can be difficult for an application to be aware of, which leads us to another option.⁹

3.4.3 Connection Establishment

The idea is to attach data to the initial TCP handshake, this way we can inform the PEP of the endpoint without needing to send it with an additional round trip time. Because of the ossified nature of TCP, changing the protocol itself is not an option. The realistic approach is reusing existing TCP functionality to append the desired data. Fortunately, only a small amount of data, less than the usual MTU, is needed to inform the PEP of the endpoint.

TCP Options Since TCP Options can be attached to a TCP connection, a possibility would be to add a new TCP Option which would specify the endpoint. This TCP Option would need to be added by a kernel module, as it is not possible to add custom TCP Options from user space. This leads to another problem, mainly how to specify from user space that we wish to use the PEP.

A possible option would be a socket option, using `setsockopt`. This however requires changes to the kernel, which raises the bar for adaptability. Another choice would be always attaching the TCP Options on connection addressed

⁹How do I solve this? An application does not know the path? So an application can't choose PEP, it can not be system wide as not all connections will have the same path. Although: if it's at the access point, all connections will actually go through it. Discussed in the non-transparent part of design.

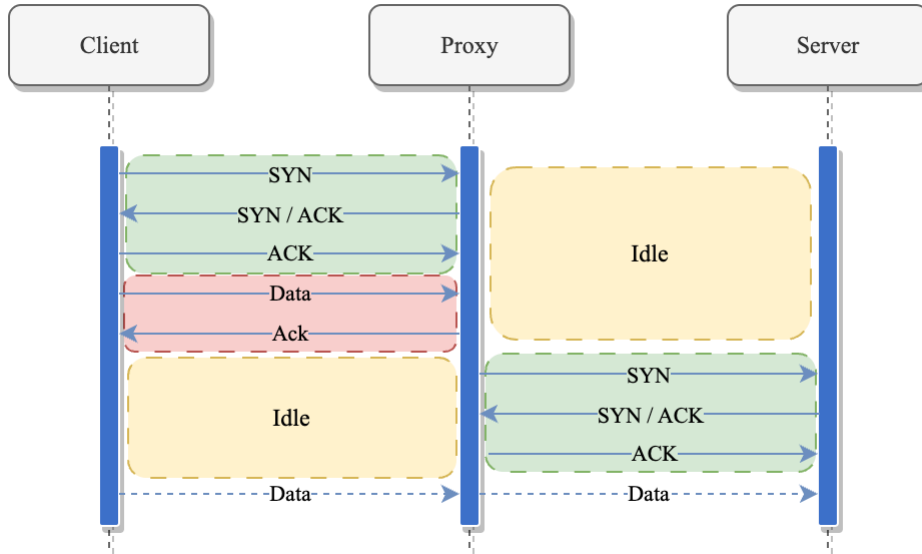


Figure 3.1: The TCP handshake procedure across PEP

to a certain port such as 80/443. This however takes away the choice from the application, and makes it system wide instead.

Finally, another significant problem is that unknown TCP Options are often seen as a threat. Firewalls may drop the packets, or the options might be stripped by intermediate nodes. [11] This creates a challenge for the implementation and usability of the PEP. If the packets may be dropped because of our custom TCP options, then the PEP will only work in certain networks and scenarios. Although we only design a proof of concept, this is a trade off that is unlikely to pay off in the end. [8] ¹⁰

TCP Fast Open Another possibility is using the existing TCP Fast Open option which can attach data to the initial TCP handshake. As discussed in the background chapter, using TCP Fast Open can reduce the amount of RTTs needed to establish a connection with both the PEP and endpoint. This requires the socket to be configured and enabled system-wide on the server machine.

Optimal Choice The most sustainable choice will be TCP Fast Open, adding new TCP Options is simply too unstable. Also, the goal of our PEP is not to change or extend TCP itself. Using TCP Fast Open also has the

¹⁰Directly quote the middlebox interaction paper section 4.4?

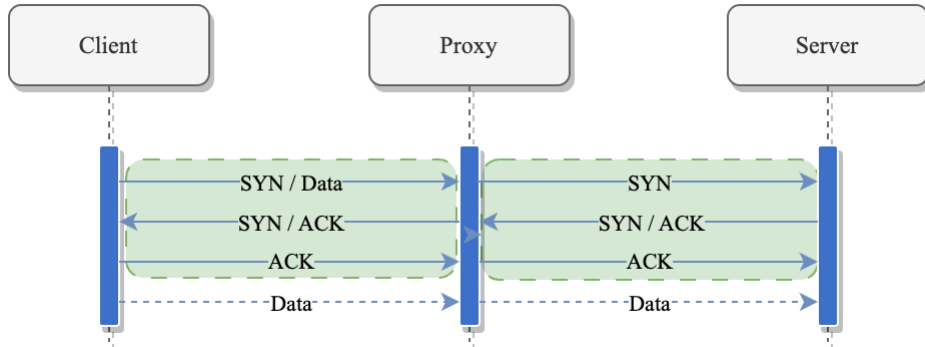


Figure 3.2: Optimal handshake across PEP (0 RTT)

advantage of being able to add meta data in the size of an MTU, which adds to the adaptability of the PEP to be extended.¹¹

3.5 Scheduling Algorithms

The ability to configure and utilize different scheduling algorithms is important for the success of the PEP. This is another choice which will bind us to Linux, as achieving the same control and configuration on other operating system, such as windows or MacOS, will be extremely difficult or even impossible. The impact will be shown in the Evaluation chapter.

3.6 Summary

Table of design decisions based on different PEP implementations compared to ours. 0RTT, Transparent, TLVs, Special ACKS, connection splitting.

PEP List				
Implementation	0RTT	Connection Splitting	Special ACKs	Transparent
milliProxy	AF	AFG	004	x
PEPDNA	AX	ALA	248	x
SnoopTCP	AL	ALB	008	x
Our PEP	DZ	DZA	012	x
Transport Converter	AS	ASM	016	x
...	AD	AND	020	x
...	AO	AGO	024	x

¹¹Rephrase last sentence.

Chapter 4

Implementation

This chapter will explore implementation of the TCP PEP, following up on the design choices mentioned in the previous chapter. The development of the PEP will give a deeper understanding of the underlying mechanisms and how they aim to better utilize the 5G bandwidth. All aspects from kernel modules, PEP architectures and additional libraries will be covered.

4.1 Kernel Module

As mentioned in the design chapter, the PEP will be written as a kernel module instead of a normal user-space program. Running and creating a kernel module requires more initial preparation than the a normal application. Firstly, the biggest change is that our PEP will now be a run as a module inside the Linux kernel instead of as a application in its own virtual environment. Injecting a module into the Linux kernel is very different from simply running a binary.

A Linux kernel module is loaded and unloaded with the help of two functions that need to be defined:

Listing 4.1.1: The basic kernel module setup code.

```
1  /* Needed by all kernel modules */
2  #include <linux/module.h>
3  #include <linux/kernel.h>
4  #include <linux/init.h>
5
6  /* entry function */
7  static int __init onload(void) {
8      return 0;
9  }
10
11 /* exit function */
12 static void __exit onunload(void) {
13
14 }
15
16 module_init(onload);
17 module_exit(onunload);
```

Listing 4.1.1 shows a basic kernel module skeleton, defining and exporting the functions `onload()` and `onunload()`. The name of the functions bear no meaning, the important parts are the macros `__init`, `module_init` and the corresponding exit macros[5]. When a kernel module is loaded the function declared with `__init` is called. Normally a application would terminate when it returns from its `main` function. Kernel modules however remain "loaded" when returning from the initialization function. This brings us to a new paradigm when programming, instead of having a running program, we install hooks and callbacks which change the default behavior of the kernel. A callback architecture can be less resource intensive as we do not need threads polling for data.

A kernel module is loaded by first compiling it into a `.ko` file and then loading with the `insmod` shell command:

```
$ insmod <module_name>.ko
$ rmmod <module_name>.ko
```

The `rmmod` is used to unload a kernel.

4.1.1 Kernel Hooks

The Linux kernel exposes many function tables and callbacks which designate what functions to call at certain events. Most drivers and congestion controllers are implemented in this manner. A predefined struct is allocated and populated with custom functions, and installed with an existing kernel function.

Listing 4.1.2: Example of a TCP congestion controller module

```

1
2 static void my_init(struct sock* sk);
3 static u32 my_ssthresh(struct sock* sk);
4 ...
5
6 static struct tcp_congestion_ops mycc __read_mostly = {
7     .init          = my_init,
8     .ssthresh      = my_ssthresh,
9     .cong_avoid    = ...,
10    .set_state      = ...,
11    .undo_cwnd      = ...,
12    .pkts_acked     = ...,
13    .owner          = THIS_MODULE,
14    .name           = "tuner",
15 };
16
17 /* entry function */
18 static int __init onload(void) {
19     return tcp_register_congestion_control(&mycc);
20 }
21
22 /* exit function */
23 static void __exit onunload(void) {
24     tcp_unregister_congestion_control(&mycc);
25 }
26
27 module_init(onload);
28 module_exit(onunload);

```

In the Listing 4.1.2 we demonstrate how a TCP congestion controller is implemented, in the context of a kernel module. This allows run-time modification of kernel behaviour, and is a programming paradigm¹ which will be useful to use when implementing the PEP.

4.1.2 Linux Version and Distribution

4.1.3 Implications

```

1 int pep_tcp_receive(struct socket *sock, u8* buffer, u32 size)
2 {
3     struct msghdr msg = {
4         .msg_flags = MSG_DONTWAIT,
5     };
6
7     struct kvec vec;
8     int rc = 0;
9

```

¹Is it a paradigm?

```

10  vec.iov_base = buffer;
11  vec.iov_len  = size;
12
13  printk(KERN_INFO "[PEP] kernel_recvmsg: calling recvmsg \n");
14 pep_tcp_receive_read_again:
15  rc = kernel_recvmsg(sock, &msg, &vec, 1, vec.iov_len,
16      MSG_DONTWAIT);
17  if (rc > 0)
18  {
19      tlv_print(buffer);
20      printk(KERN_INFO "[PEP] kernel_recvmsg: recvmsg returned %d\n", rc);
21      return rc;
22  }
23  if(rc == -EAGAIN || rc == -ERESTARTSYS)
24  {
25      goto pep_tcp_receive_read_again;
26  }
27
28  printk(KERN_INFO "[PEP] kernel_recvmsg: recvmsg returned %d\n", rc);
29  return rc;
30 }

```

Listing 4.1: kernel_recvmsg wrapper for receiving for TCP msgs

4.2 TLV Library

Regarding the endpoint addressing and selection by the client, a custom shared library is a good choice.² The goal is to keep the client code as simple and close to its original state as possible, but still be able to communicate the endpoint, potential options and meta-data to the PEP. Additionally, we want to send this information by using TCP Fast Open which has a similar connection routine as default sockets do.

Normally a socket would first create, connect and then send data using the `send` system call. The creation of a socket is the same for both default and TCP Fast Open. Which leaves us with connection as the main problem, the way we connect to a host using TCP Fast Open is by skipping `connect` and instantly jump to `sendto`. As we can see from the socket system calls, both `connect` and `sendto` take a `struct sockaddr` in as a parameter. This defines the endpoint to which you want to connect. `sendto` has a flag option which allows the configuration of how messages are sent, and if we supply the `MSG_FASTOPEN` flag, `sendto` will automatically connect and deliver the given message within the handshake. Subsequent uses of `send` will function

²Rewrite this.

as if the `connect` function was used.

Important socket system calls

```
int connect(
    int sockfd,
    const struct sockaddr *addr,
    socklen_t addrlen
);

ssize_t send(
    int sockfd,
    const void *buf,
    size_t len,
    int flags
);

ssize_t sendto(
    int sockfd,
    const void *buf,
    size_t len,
    int flags,
    const struct sockaddr *dest_addr,
    socklen_t addrlen
);
```

4.2.1 Custom connect function

The library will replace the original `connect` with an custom implementation `pep_connect`. The original `connect` and `sendto` have a lot of parameters in common, specifically the `const struct sockaddr` which is used to identify an endpoint. In the context of the PEP, this would identify the final endpoint to which the client wants to connect. The goal of the PEP `connect` function is to replace the `sockaddr` given by the client with one that identifies the PEP, but still forward the original `sockaddr` to the PEP to establish the proxy connection.

The signature of the our custom implementation mimics the original `connect`. The main difference is the addition of a `flags` parameters for easier customization. Inside our custom function we allocate space for a new `struct sockaddr` which we will fill with the IP address and port of the PEP, while at the same time we create a message with original IP address and port of the endpoint. Finally we call `sendto` with our message and the new `struct sockaddr`, using `MSG_FASTOPEN` to both connect and deliver the message.

The custom connect function signature

```
int pep_connect(  
    int sockfd,  
    const struct sockaddr* addr,  
    socklen_t len,  
    int flags  
);
```

4.2.2 TLV

A good choice for sending options and meta-data is in the form of TLVs, formally known as Type-length-value options. The idea is that all options can be defined by a Type, Length and Value. The type defines the type of an option, what types exists and what they mean are up to the users of the library to decide. Common types are "Version", "Error", etc, adding new types is very easy and requires little modification. The TLV is practically implemented as its own message, but can also be appended at the start of a transmission like a header [2]³.

TLV structures

```
struct __tlv_header {  
    unsigned char version;  
    unsigned char len;  
    unsigned short magic;  
};  
  
struct tlv {  
    unsigned char type;  
    unsigned char length;  
    unsigned short value;  
    unsigned int optional;  
};
```

TLV Implementation In our design, TLVs are structured as a continuous buffer, consisting of a TLV header followed by subsequent options. This header provides details on the version, the number of options, and a unique magic number for validation. The **type** spans 1 byte, which means we limit ourselves to 255 possible types. The current implementation only uses 6, which means we have enough space for future extensions. The **length** variable is mainly used to indicate an optional data segment called **optional**. The size of the default value is 2 bytes with an additional option of size 4 bytes. All together the struct uses 8 bytes or 64 bits, which mostly comes from the fact we need atleast 6 bytes for the IP address and port alone.

³Reference this more directly as we adapt the idea of TLVs from this paper.

Problems using TFO When using TCP Fast Open ... instant return with no confirmation of a successful connection. ⁴

4.2.3 TLV Options

The options of the TLVs define the functionalities a PEP can provide, for our PEP we only need 6 options. The basic **info** and **error** options are included alongside some information about the TCP connection such as extended headers. The most important type is **connect**, it specifies a port and IP address and is used to communicate the endpoint to the PEP. A TLV message can include as many options as a client wants.

```
enum __tlv_types {
    TLV_INFO = 0x1,      // Info TLV
    TLV_CONNECT = 0xA,   // Connect TLV
    TLV_EXT_TCP = 0x14,   // Extended TCP header
    TLV_SUPP_EXT = 0x15,  // Supported TCP extension
    TLV_COOKIE = 0x16,   // Cookie TLV
    TLV_ERROR = 0x1E     // Error TLV
};
```

4.2.4 Shared Library

The PEP TLVs are implemented as a shared library which is both used by the PEP itself and applications. The applications will use the library to create TLVs for connecting to the PEP, while the PEP uses the library to validate and read the TLV options. A shared library can be created by passing the `-shared` flag to the linker.

⁵

```
$ gcc file.c <path>/<lib>.so -o file.o
```

4.3 PEP

Brief description of the PEP internals, sockets, queues, forwarding, hooks.

4.3.1 Architecture

The PEPs architecture is mainly based on a main server and multiple socket tunnels. The main server acts as the entry point of the PEP, clients will connect to the main server which will in turn connect to the endpoint. The server consists of a `pep_state` which holds the server socket, work queues

⁴Lots to add here...

⁵More about how to create shared libraries, include files etc. How to bind lib to application.

and a list of tunnels. The server socket accepts new clients and reads their TLV header, if no header is present the connection will be closed. After successfully reading the TLV, a new socket is created and a connection is attempted to the endpoint specified by the TLVs.

```
struct pep_state {
    atomic_t state;
    struct socket* server_socket;
    struct workqueue_struct* accept_wq;
    struct workqueue_struct* forward_c2e_wq;
    struct workqueue_struct* forward_e2c_wq;
    struct work_struct accept_work;
    struct list_head tunnels;
    unsigned int total_tunnels;
};
```

Figure 4.1: PEP State Structure Code

Tunnels After the endpoint connection is established, the PEP will create a **tunnel**. A **tunnel** consists of 2 sockets, where data is transferred between them. Additionally to the sockets, a **tunnel** also holds the information about the sockets and the proxy connection, this includes total amount of data transferred.

PEP Tunnel Structure

```
struct pep_tunnel {
    unsigned int id;
    struct pep_connection client;
    struct pep_connection endpoint;
    int total_client;
    int total_endpoint;
    struct work_struct c2e;
    struct work_struct e2c;
    struct list_head list;
    struct pep_state* server;
    int state;
    int recv_callbacks;
    int packets_fowarded;
};
```

[PICTURE OF ARCHITECTURE]

4.3.2 Kernel Sockets

Normally an application would interact with a socket descriptors when sending and receiving data. However, inside the kernel we have access to the actual sock and socket structures. This gives us full access to all functionality and meta-data a socket can offer, such as `sk_buff` queues, callbacks and statistics like `sk_drops`. An `sk_buff`, which stands for socket buffer, is the kernel struct that holds the information about a packet. It includes both the header and data of a packet and is created when the kernel receives a packet. After that it is routed to the corresponding socket.

```
struct sock {
    atomic_t sk_drops;
    void* sk_user_data;
    ...
    struct sk_buff_head sk_error_queue;
    struct sk_buff_head sk_receive_queue;
    ...
    struct socket *sk_socket;
    ...
    void (*sk_state_change)(struct sock *sk);
    void (*sk_data_ready)(struct sock *sk);
    void (*sk_write_space)(struct sock *sk);
    void (*sk_error_report)(struct sock *sk);
    ...
};
```

Figure 4.2: Kernel Sock Structure

Socket Operations

Socket Callbacks Especially of interest is the callback function `sk_data_ready`. It is called whenever a `sk_buff` is received by a socket. That is the case for any kind of packet, not only user data but also includes the TCP handshake packets. This callback can be overwritten by a custom implementation, which is useful to detect any interactions on the socket. For example one could inspect or manipulate headers before calling the original `sk_data_ready` function. All callbacks take themselves as a parameters, thereby giving access to the socket state.

Socket User Data Kernel sockets allow modules to add extra information to a specific socket. The pointer `sk_user_data` can be used to point to any data defined by a module. This in combination with the callbacks

is a powerful tool for customizing socket behavior. This allows us to add additional state information to the socket.

Benefit of using kernel moduels -> direct access to socket struct instead of an fd. socket struct, user_data, data_ready callback Code snippets

4.3.3 Work Queues

To handle multiple concurrent events, the PEP uses **work queues**. A work in the Linux kernel is a way of handling kernel threads. They allow for a more reactive approach to threads, as a work can be queued on demand and execute simple tasks. A work is usually queued into a **work queue**. Each **work queue** represents a task and works which are queued will wait in the queue till they can be run. A task is defined as a function, to which context can be added through a **work** parameter.

Figure 4.3: Work struct from Linux - workqueue.h

```
struct work_struct {
    atomic_long_t data;
    struct list_head entry;
    work_func_t func;
#ifdef CONFIG_LOCKDEP
    struct lockdep_map lockdep_map;
#endif
};
```

Works A work is defined by **work_struct** (see Figure 4.3) which holds information associated with the work, most importantly the **work_func_t func**. **func** must be a pointer to a function which takes a **struct work_struct** as parameter. This is the function which will be called when a work is scheduled. The work structure should be created by the user and not be allocated on the stack as external services need access to it. Normally the work structure will be part of another structure as it is in Figure 4.1.

4.3.4 Work State problem

Since we do not have a "main" thread for each connection, and we want to avoid "global" variables, we do not have a stack state, all events are "async" and will not have access to our PEP states as we only get sock structs.

As described in the PEP Tunnel Structure (see above struct 4.1), the PEP has 3 main work queues:

```
struct workqueue_struct* accept_wq;
```



```
struct workqueue_struct* forward_c2e_wq;
struct workqueue_struct* forward_e2c_wq;
```

Accept Work Queue The main work queue for the server is the accept work queue. When a client attempts a connection to the PEP server we want to receive that notification and queue a accept work. This is an alternative to have a thread blocking on accept. The notification can be achieved by replacing the `sk_data_ready` with a custom function which checks the TCP state and queues a accept work.

Listing 4.3.1: Accept callback function

```
1 void pep_listen_data_ready(struct sock* sk)
2 {
3     struct pep_state* server;
4
5     read_lock_bh(&sk->sk_callback_lock);
6     server = sk->sk_user_data;
7
8     /* Queue accept work */
9     if(sk->sk_state == TCP_LISTEN){
10         queue_work(server->accept_wq, &server->accept_work);
11     }
12     read_unlock_bh(&sk->sk_callback_lock);
13
14     default_data_ready(sk);
15 }
```

The function `pep_listen_data_ready` (see Listing 4.3.1) outlines the process to set up accept works. We retrieve the PEP server state from the socket `sk_user_data` variable, afterwards we check the socket state for `TCP_LISTEN` which indicates that the socket is ready to accept a connection. If the socket has the correct state we queue the `accept_work` on the `accept_wq` work queue, which is part of the PEP server.

Packet Forwarding Queues The main work queue for the server is the accept work queue.

Different work queues in the PEP... [PICTURE PERHAPS?] Major implementation choice over "active" threads.

4.3.5 Client Sockets - Endpoint Sockets

How forwarding works. code snippets

4.3.6 Using Netfilter

Forwarding using Netfilters, why we dont want this.

4.3.7 PEP Connections

How handling of multiple connections work Freeing? Closing?

4.3.8 Userspace?

Could this be implemented in user-space?

4.3.9 Threads Vs. Callbacks

Small discussion around that?

4.4 Memory

Memory Managment in C, why its important, how we deal with it.

Chapter 5

Evaluation

5.1 Initial configuration

Sender → Receiver → Receiver

Data being pushed from Sender to receiver, file size, speed, delay.

5.1.1 Traffic Control Options

Linux has support for network interface configurations using the TC (traffic control) command. TC allows the configuration of packet scheduler, bandwidth, delay and jitter etc. These options combined with the fact that each network interface can have its own configuration, allows for very precise testing environments.

fq_codel does not allow the configuration of delay, this means we have to configure the delay on the path of the ACKS? We have to configure the delay on sender facing interface cards. ¹

5.1.2 Scheduling Algorithms

The choice of scheduling algorithm is very important for our test scenarios. As it will greatly affect the results of our tests, we will compare some against each other. The main goal is to highlight the effect and find the optimal algorithms for our PEP.

FIFO In our test case FIFO will have the effect of creating up a queue at our PEP. This is detrimental for the interactive UDP flow as it will be stuck in the queue, building up delay. This behavior can be explained by the fact that the non-interactive flow has a much higher sending rate than the interactive flow, thereby quickly filling the finite queue with non-interactive packets.

¹Picture of testbed setup

FQ CoDel: IMPORTANT FQ CoDel has a solution for this problem by providing a fair queuing mechanism.

PFIFO Another alternative is Priority FIFO (PFIFO). As the name suggests it combines the concepts of a basic FIFO queue with priorities. This can reduce delay

5.1.3 Interactive vs PEP

Our first experiment consists of having a interactive flow (100 byte UDP packets at 2kBps) competing with a file transfer, one default end to end and one through our PEP. Highlighting some of the initial differences between an end to end connection and a PEP.

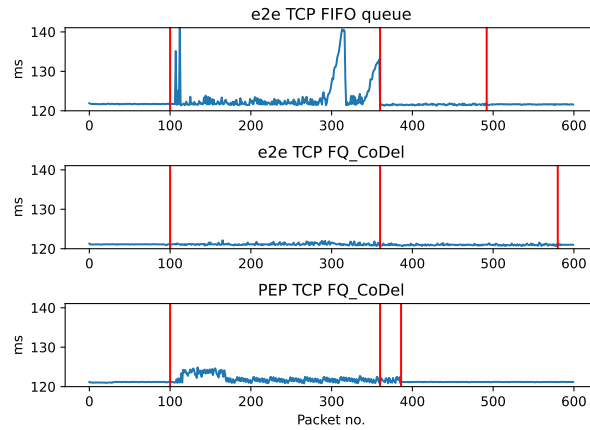


Figure 5.1: Interactive UDP traffic

5.1.4 PEP vs E2E tests

The first test consists of evaluating our PEP against a default TCP end to end (E2E) connection, while also highlighting the difference a packet scheduler can make. Fig. 5.1 shows the results, the red lines represent important events in the time-line. The first line represents the start of a file transfer, the second shows a bandwidth change from 10mbit to 75mbit, while the last line shows when the file transfer finished.

The first time-line shows an end to end TCP transfer using a FIFO queue, in this case BFIFO.

On the second timeline we see the behavior of an end to end connection using FQ CoDel. MORE The last timeline shows the PEP using FQ CoDel. Looking at the graph we can see two important differences between the

default end to end TCP and the PEP. Firstly, the PEP has higher latency fluctuations than the E2E connection, shown by the blue lines on the graph.

5.1.5 10x10 tests

To further evaluate the PEP we conducted an experiment where we have 1-10 flows competing, once using the PEP and once end to end. The goal is to see how competing flows affect the behavior of our PEP

5.1.6 Spike

Chapter 6

Conclusion

6.1 Future Work

Bibliography

- [1] S. K. Agrawal and Kapil Sharma. 5g millimeter wave (mmwave) communications. In *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)*, page 3630–3634, Mar 2016.
- [2] Olivier Bonaventure, Mohamed Boucadair, Sri Gundavelli, SungHoon Seo, and Benjamin Hesmans. 0-RTT TCP Convert Protocol. RFC 8803, July 2020.
- [3] David Borman. TCP Options and Maximum Segment Size (MSS). RFC 6691, July 2012.
- [4] Kristjon Ciko, Michael Welzl, and Peyman Teymoori. Pep-dna: A performance enhancing proxy for deploying network architectures. In *2021 IEEE 29th International Conference on Network Protocols (ICNP)*, pages 1–6, 2021.
- [5] J.-M. De Goyeneche and E.A.F. De Sousa. Loadable kernel modules. *IEEE Software*, 16(1):65–71, 1999.
- [6] Wesley Eddy. Transmission control protocol (tcp). Request for Comments RFC 9293, Internet Engineering Task Force, Aug 2022.
- [7] Jim Griner, John Border, Markku Kojo, Zach D. Shelby, and Gabriel Montenegro. Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations. RFC 3135, June 2001.
- [8] Michio Honda, Yoshifumi Nishida, Costin Raiciu, Adam Greenhalgh, Mark Handley, and Hideyuki Tokuda. Is it still possible to extend tcp? In *Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference*, page 181–194, Berlin Germany, Nov 2011. ACM.
- [9] Toke Høiland-Jørgensen, Paul McKenney, dave.taht@gmail.com, Jim Gettys, and Eric Dumazet. *The Flow Queue CoDel Packet Scheduler and Active Queue Management Algorithm*. Number RFC 8290. Jan 2018.

- [10] Brian W. Kernighan and Dennis M. Ritchie. *The C Programming Language*. Prentice Hall Professional Technical Reference, 2nd edition, 1988.
- [11] Alberto Medina, Mark Allman, and Sally Floyd. Measuring interactions between transport protocols and middleboxes. In *Proceedings of the 4th ACM SIGCOMM conference on Internet measurement*, page 336–341, Taormina Sicily, Italy, Oct 2004. ACM.
- [12] Michele Polese, Marco Mezzavilla, Menglei Zhang, Jing Zhu, Sundeep Rangan, Shivendra Panwar, and Michele Zorzi. milliproxy: A tcp proxy architecture for 5g mmwave cellular systems. In *2017 51st Asilomar Conference on Signals, Systems, and Computers*, pages 951–957, 2017.
- [13] Cristian García Ruiz, Antonio Pascual-Iserte, and Olga Muñoz. Analysis of blocking in mmwave cellular systems: Application to relay positioning. *IEEE Transactions on Communications*, 69(2):1329–1342, Feb 2021.
- [14] W. V. Wathsala, Buddhika Siddhisena, and Ajantha S. Athukorale. Next generation proxy servers. In *2008 10th International Conference on Advanced Communication Technology*, volume 3, pages 2183–2187, 2008.
- [15] Michael Welzl. Network congestion control: Managing internet traffic. *Network Congestion Control: Managing Internet Traffic*, pages 1–263, 05 2006.
- [16] Michael Welzl, Dimitri Papadimitriou, Bob Briscoe, Michael Scharf, and Michael Welzl. Open Research Issues in Internet Congestion Control. RFC 6077, February 2011.