eBPF for Mesh Network Monitoring

Carlos Tiago Gomes Pinto
Mestrado em Engenharia de Redes e Sistemas Informáticos
Departamento de Ciência de Computadores
2022

Orientador
Rui Pedro de Magalhães Claro Prior, Professor Auxiliar, FCUP

Supervisor
Eduardo Filipe Amaral Soares, Estudante de Doutoramento, FCUP

Todas as correções determinadas pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

Porto, ______/______/_________

Sworn Statement

I, Carlos Tiago Gomes Pinto, bearer of the mechanographic number 201606191, enrolled in the Master Degree Network and Information Systems Engineering at the Faculty of Sciences of the University of Porto hereby declare, in accordance with the provisions of paragraph a) of Article 14 of the Code of Ethical Conduct of the University of Porto, that the content of this dissertation reflects perspectives, research work and my own interpretations at the time of its submission.

By submitting this dissertation, I also declare that it contains the results of my own research work and contributions that have not been previously submitted to this or any other institution.

I further declare that all references to other authors fully comply with the rules of attribution and are referenced in the text by citation and identified in the bibliographic references section. This dissertation does not include any content whose reproduction is protected by copyright laws.

I am aware that the practice of plagiarism and self-plagiarism constitute a form of academic offence.

Carlos Tiago Gomes Pinto

30/09/2022

Abstract

Being able to monitor the changes in a network is an important part of experimentation and troubleshooting in the investigation field. In this work we explore eBPF, a technology available in the Linux kernel that can be used not only for monitoring, but also for the creation of monitoring tools, as well as the different libraries and frameworks available to help with eBPF usage.

Using eBPF, we develop a tool for monitoring the creation, modification, and removal of paths in Institute of Electrical and Electronics Engineers (IEEE) 802.11s mesh networks in Linux, for use with wireless interfaces that use the softMAC implementation included in the kernel, mac80211. The tool captures events that change paths and associate them with the packets that triggered the changes, whenever applicable. It provides an interactive graphical user interface that gathers information collected in the different nodes and presents it to the user. Along with the development, we also present the tests and work that was done in the exploration of eBPF and the mac80211 subsystem of the Linux kernel.

Resumo

A capacidade de monitorizar mudanças numa rede de computadores é uma parte importante da experimentação e resolução de problemas na área da investigação. Neste trabalho exploramos o eBPF, uma tecnologia disponível no *kernel* Linux que pode não só ser usada para monitorização, mas também para a criação de ferramentas de monitorização, e as diferentes bibliotecas e *frameworks* disponíveis para ajudar com o uso do eBPF.

Usando eBPF, criamos uma ferramenta para monitorizar a criação, modificação, e remoção de caminhos em redes *mesh* IEEE 802.11s no Linux, para uso com interfaces sem fios que usam a implementação softMAC incluída no kernel, mac80211. A ferramenta captura eventos que alteram caminhos e associa-os com os pacotes que provocaram as mudanças, sempre que aplicável. Fornece também uma interface gráfica que junta a informação gerada nos diferentes nós e apresenta-a ao utilizador. Em conjunto com o desenvolvimento, também apresentamos os testes e trabalho realizados na exploração do eBPF e do subsistema mac80211 do *kernel* Linux.

Acknowledgements

I want to thank first and foremost my advisors Rui Prior and Eduardo Soares for the tremendous help they have given me throughout these last twelve months. I would also like to thank the Instituto de Telecomunicações (UIDB/50008/2020) for hosting this work.

I also want to thank my parents for the support they have given me throughout my whole life, and my friends for the joyous times we spent together.

Contents

List of Tables

List of Figures

Listings

Acronyms

AODV	Ad-hoc On-Demand Distance Vector
ARP	Address Resolution Protocol
BCC	BPF Compiler Collection
BPF	Berkely Packet Filter
BTF	BPF Type Format
CO-RE	Compile Once - Run Everywhere
DWARF	Debugging With Attributed Record Formats
GUI	Graphical User Interface
HWMP	Hybrid Wireless Mesh Protocol
IEEE	Institute of Electrical and Electronics Engineers
JIT	Just-in-Time
LTS	Long-Term Support
MAC	Media Access Control
PHY	Physical Layer
QoS	Quality of Service
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network
XDP	eXpress Data Path

Chapter 1

Introduction

Monitoring and observability have always been important aspects in the field of computer systems. They can be found everywhere, being used to determine the performance and health of systems by administrators, used by programmers in the form of debuggers, and even in research, to analyse new technologies and verify that they are working as expected.

Several monitoring tools have been created over the years for all kinds of purposes and hardware, but as components and software become more advanced, these tools end up having to be replaced or updated. One of these newer tools that has been gaining popularity in the last few years is eBPF.

eBPF is a technology that started out as the Berkely Packet Filter (BPF), which was a tool for writing efficient packet filters. It has since been improved, having received new capabilities, and also updated in order to take advantage of newer hardware, transforming into eBPF. eBPF allows users to write programs that run on certain events of the Linux kernel, allowing not only for monitoring of its internals, but also enhancing its capabilities without the need to use kernel modules, all of this while still ensuring the security and stability of the kernel. Because eBPF can not only be used to access the internals of a system, but also intercept the packets that system sends and receives, eBPF can be used to monitor a whole network of systems.

One example of how eBPF can be used, is to monitor a network of systems in IEEE 802.11s wireless mesh networks, by probing the functions in the Linux kernel related to these mesh networks in each of the systems in said networks.

1.1 Aims and Objectives

The main objective of this work will be to study eBPF, seeing what it can and can not do, and determining how it can be used for network observability in experiments, particularly in Institute of Electrical and Electronics Engineers (IEEE) 802.11s networks. We will then proceed with the development of a tool that uses eBPF to demonstrate the type of monitoring applications that can be built with this technology, revealing the exploratory work that was done in order to realise this tool.

1.2 Organization

This thesis will start with the background in Chapter 2, where we will go over Institute of Electrical and Electronics Engineers (IEEE) 802.11 and IEEE 802.11s mesh networks, as well as what eBPF is in more detail, and explaining the different tools that can used to take advantage of this technology.

Next, Chapter 3 will cover the exploratory part of this work, where we mention the steps we took to understand how the Linux kernel's implementation of the data link layer for IEEE 802.11 networks (mac80211) deals with IEEE 802.11s mesh networks, mentioning some of the tests used for this purpose and to get some experience with writing eBPF programs.

In Chapter 4 we talk about the development of the program that was written to serve as an example of a tool that uses eBPF for network monitoring, going over each section of its code. We also introduce the companion program that was created to view the results generated by the main program.

Some of the tests that were used during development are explained in detail in Chapter 5, where we analyse what was learned from them, and the decisions taken based on their results, including the final test that was performed with the finished program running in real hardware.

Finally, in Chapter 6 we take a look at what we managed to accomplish, and the limitations we had to settle for. We also mention parts of our programs that could be improved upon, together with possible solutions.

There is no “State of the Art” chapter as there was no state of the art surrounding the use of eBPF for monitoring IEEE 802.11s mesh networks at the start of this work.

Chapter 2

Background

This chapter will introduce the IEEE 802.11 network technical standard together with IEEE 802.11s mesh networks, as well as explain eBPF in detail, and reference the major libraries and frameworks used to facilitate the development of eBPF programs.

2.1 Mesh Networks

The Institute of Electrical and Electronics Engineers (IEEE) 802.11 is a standard that is part of the IEEE 802 group of technical standards, and specifies the Media Access Control (MAC) and Physical Layer (PHY) protocols used to implement communication of computers in a Wireless Local Area Network (WLAN). The standard has evolved over the years since its first publication in 1997, and the revision published in 2012 incorporated several amendments, one of which was 802.11s, which introduced a definition for the creation of wireless mesh networks in a WLAN [20].

A IEEE 802.11s wireless mesh network is a network of devices, called mesh stations, that are interconnected to each other, as shown in Figure 2.1, with these connections being formed and destroyed dynamically by the stations themselves, without the need for a central station to manage these connections. Links are established when stations are able to communicate directly, and data that needs to travel a large distance is fed through the connections of the mesh network in a series of hops, allowing for the communication of stations that are too far apart to communicate directly. Some of the stations in a mesh network can also act as portals to other networks, such as the Internet, providing, in this example, Internet access to the whole network. These are referred to as mesh portals [27].

The layer 2 routing protocol defined by IEEE 802.11s that is used to create and destroy these links is known as Hybrid Wireless Mesh Protocol (HWMP) [20]. In this protocol, each station discovers other stations and manages a table of its existing connections through a usage of the peer link management protocol, where a station transmits beacons (frames with information about a network), and other listening stations that want to become members of the same mesh

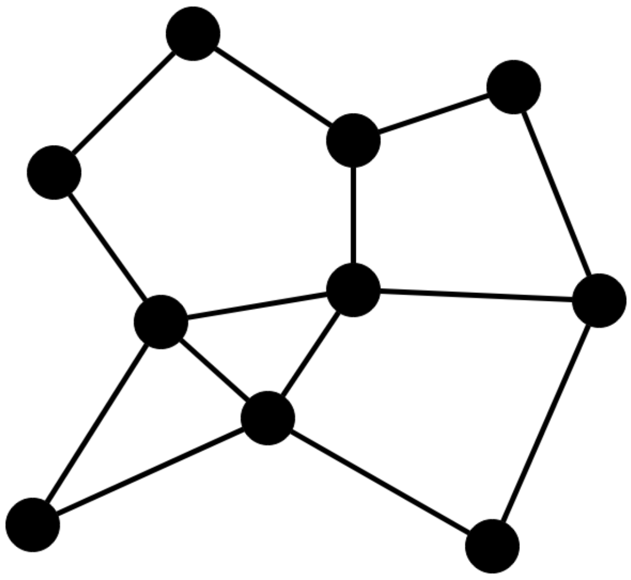


Figure 2.1: Example of an IEEE 802.11s mesh network

network reply to these transmissions. The table used to store these connections keeps not only the direct connections the station has, but also the connections to stations that are farther away, keeping an additional **nexthop** value, which holds the address of the station that is directly connected to the source that provides the best path to the destination, as seen in Figure 2.2. As the name suggests, this protocol is hybrid, and it consists of two main components. A proactive protocol, which is a tree-based hierarchical routing protocol, and a reactive protocol, which is a modification of the Ad-hoc On-Demand Distance Vector (AODV) [26] routing protocol [19].

The proactive protocol works by having a station act as a designated root node, and is only used when stations want to communicate with the root node or with devices outside the mesh network [3, 18]. When stations need to communicate with other stations in the mesh network, the reactive protocol is used. In this protocol, when a station needs to communicate with another, it broadcasts a **Path Request** message with the MAC address of the destination. Intermediary stations rebroadcast this message while keeping information from the transmitter of the message, in order to reach back with the response. When the destination receives it, it updates its path to the source and sends back a **Path Reply** in unicast [3].

In the Linux kernel's implementation of the data link layer for IEEE 802.11s mesh networks, the connections between stations are known as **mesh paths**, and the table where each system tracks these connections is referred to as the **mesh path table**.

2.2 eBPF

The Berkely Packet Filter (BPF) started out, as the name would suggest, as a packet filtering tool, used only to accept or reject packets. This tool was created because the existing packet filters were inefficient, having been developed for older hardware. BPF not only changed the design of

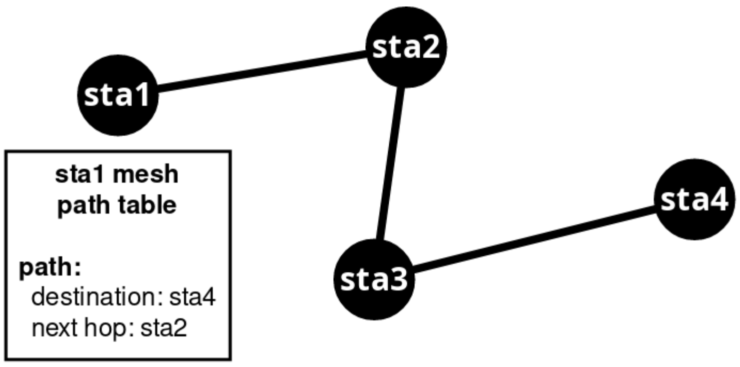


Figure 2.2: Example of a mesh path

the filter evaluator used, replacing the stack-based one used by the original Unix packet filter with a register-based evaluator, but it also changed the buffering strategy, resulting in improved performance, among other things [23].

BPF filters packets using a directed acyclic control flow graph, where nodes represent packet field predicates, and edges are control transfers. So, for example, nodes would have checks in the form of "ether.type=IP", and edges would be either a "yes" or a "no", with the flow going along the path of the correct result. This approach is quite efficient, as it allows a BPF program to create a single flow graph that passes through several predicates, having to parse each packet a single time, and ends in either a “True” or “False”, deciding whether a packet should be processed or not, as seen in the example in Figure 2.3 [23]. These filters can be written by system administrators, and then run inside the Linux kernel, which allows BPF to check the packets before they are processed by the kernel.

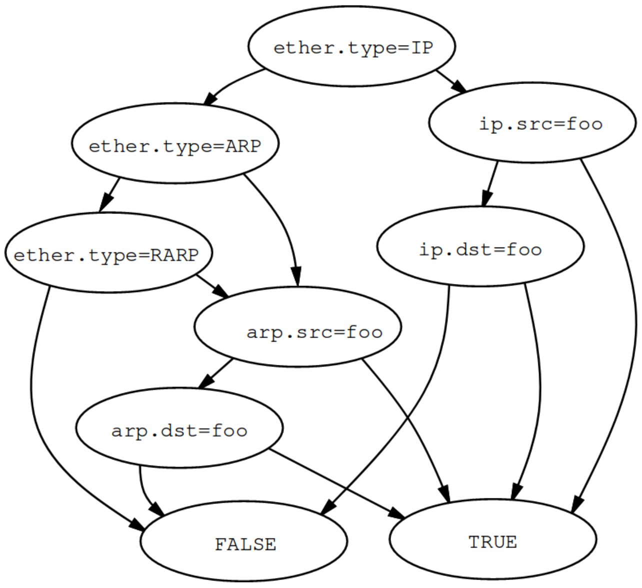


Figure 2.3: Example of a BPF program (Source: [23])

Seeing the potential of being able to write programs to run inside the kernel, Alexei Starovoitov decided to improve BPF, creating eBPF [1], which used to be an acronym for “extended BPF”, although that is no longer the case [13]. Instead of simple flow-chart-like programs that can only be used for packet filtering, eBPF now allows users to write more complex programs that can involve arithmetic, structures, and pointers.

eBPF programs are executed on events, like function calls and network events, through the use of, for example, **probes**, which are programs inserted dynamically at the beginning or end of functions, with **kprobes** being used for functions inside the kernel, and **uprobes** for functions in user-space, as well as **tracepoints**, which are static points already present in the kernel introduced by the kernel developers, which can be seen in Figure 2.4. These programs are loaded into the kernel with the `bpf` system call and then pass through a verifier that ensures that they are safe to run and do not get stuck in loops, checking if there are any unreachable instructions, infinite loops, or instructions that harm the system. Naturally, the verifier introduces some limitations to eBPF programs, such as a limited number of instructions per eBPF program (Linux version 5.2 increased this number from 4096 to one million [10]), disallowing conditional loops, and requiring root privileges for most programs [2]. Finally, these programs are passed onto a Just-in-Time (JIT) compiler that optimises their performance by translating the code into machine specific instructions. Also, because eBPF is part of the Linux kernel, there is no need for external modules to be installed to run these programs [13].

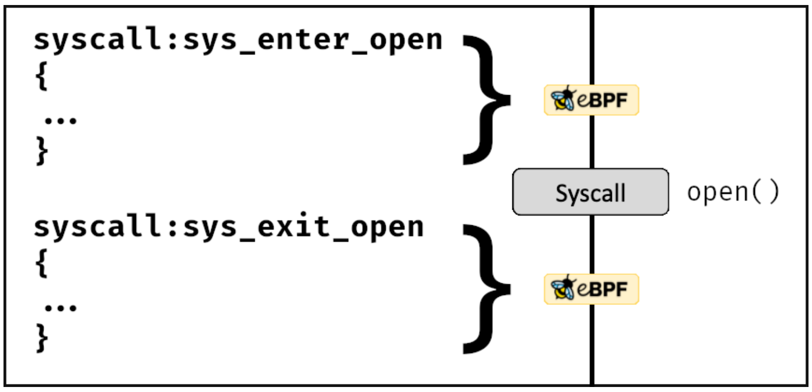


Figure 2.4: Example of eBPF tracepoints

eBPF also introduces mechanisms to help with development. Probes have already been mentioned, but it also provides BPF maps, which allow programs to save data temporarily in kernel-space, enabling sharing of information across probes and to user-space [2].

Not only that, but eBPF can also be used to write eXpress Data Path (XDP) programs. XDP is a framework that allows for processing packets at the lowest possible level, even before the kernel itself can process them. Some network cards even support using XDP in the controller itself, allowing for super fast processing of packets. This, however, has limitations as well, since the programs are written in a restricted variant of C, because they need to be translated into eBPF byte-code, and XDP can only be used in packet reception [29].

eBPF has become an important tool in the last few years, having been used for discovery of dependencies in network services [28], taking advantage of its small performance overhead, as well as monitoring traffic in Open vSwitches [32], proving to be a better choice against other monitoring solutions thanks to its code verifier, which ensures that buggy eBPF code will not crash or otherwise severely interfere with a system.

2.3 BCC

The BPF Compiler Collection (BCC) is a toolkit with the purpose of allowing the creation of eBPF programs more easily, with front-ends in both Lua and Python. This tool allows for easier development of eBPF programs, as it abstracts the use of the Berkely Packet Filter (BPF) system call, replacing this with C-like code, which is then loaded into the system with calls from a Python or Lua program. The toolkit is well documented, and it also comes with some pre-made programs, which serve as examples of useful eBPF programs [8, 17].

The ease of use comes at a cost, however, as BCC embeds the LLVM toolchain to compile programs, which leads to heavy processor and memory usage on compilation [22, 30]. This can become a problem since BCC compiles programs every time they are run. Not only that, but BCC also requires the system to have the kernel header packages installed, which not only occupies extra space on the system to hold these packages [22, 30], but can also be problematic, especially when working with multiple Linux distributions, where the kernel header packages' content can be different.

BCC used to be the primary choice for development of complex eBPF programs, but it is now considered deprecated, with newer programs using libbpf together with Compile Once - Run Everywhere (CO-RE) [4].

2.4 bpftrace

IO Visor, the project behind BPF Compiler Collection (BCC), has also introduced bpftrace, which is a high-level language for tracing the Linux kernel that uses eBPF [11]. Unlike BCC, it is not a library, so no extra code is needed to run programs. The user can simply write their bpftrace program and execute it directly with the `bpftrace` command. However, it does not have an API that allows for manipulation of data outside bpftrace. Also, like BCC, bpftrace needs the kernel header packages for structure and other type definitions [11].

Due to being less verbose than BCC, bpftrace is much easier to work with, but because of its lack of API, which only allows to send information to the standard output, it becomes useful only for programs that do not need to send data to user-space. Still, if data needs to be sent to user-space, bpftrace is still useful for small tests and to quickly find all the available probes and tracepoints through the usage of its `-l` flag, which lists all probes.

2.5 perf

perf is a Linux command used to analyse the Linux kernel's performance. perf provides several subcommands that can record events, count the number of events in a given timeframe, see events in real time, etc [25]. perf was originally created before eBPF, but it now uses it for tracing with tracepoints and probes [24], and eBPF itself uses perf, for example, to send data from BPF maps to user-space using perf buffers [9].

perf is very similar to bpftrace, and like it, it is most suitable for smaller scripts instead of big applications, suffering from the same disadvantages as bpftrace.

2.6 libbpf and CO-RE

libbpf is a library written in C/C++ designed to allow loading and interacting with eBPF programs [21]. It is considered an alternative to BPF Compiler Collection (BCC), but with many advantages over it. libbpf abstracts many aspects of eBPF, just like BCC, but, unlike BCC, which compiles the eBPF programs at runtime, libbpf allows programs to be compiled into eBPF bytecode [21, 22], eliminating the need of several dependencies on the system in which the programs are being executed. Not only that, but libbpf doesn't rely on kernel headers, instead using a header file that contains multiple kernel structure definitions and types, eliminating the need for kernel headers to be installed on the system [22]. The drawback is that it is not as well documented as BCC, having almost only examples to serve as aid in development.

Compile Once - Run Everywhere (CO-RE) is an approach implemented by libbpf that allows the creation of portable eBPF programs, meaning that programs only need to be compiled once, and can then be deployed across multiple systems, working even if these systems differ in architecture and kernel version [5, 7]. This is possible because of the BPF Type Format (BTF). BTF is a format that encodes debug information, akin to Debugging With Attributed Record Formats (DWARF), but in a more compact and efficient manner, and is used to provide information like structure offsets, which can then be used by CO-RE to relocate the eBPF bytecode as needed by the kernel version being used [6]. This means that the kernel needs to be compiled with support for BTF. Thankfully, because BTF support only amounts to about 1.5 megabytes in increase to the kernel image, most distributions already compile their kernels for x86 architectures with the support [4]. Similarly to BCC, a program needs to be created in order to load eBPF programs, but CO-RE also requires a file containing the structures and type definitions used in the kernel to be generated (although this only needs to be done once) [12].

The problem with CO-RE is pretty much the same as libbpf: it is not well documented, and most of its documentation consists of a few blog posts made by its main developer. The blog posts are actually quite well written, but they only touch on the general uses of elements from CO-RE with a few examples. For more specific questions a developer might have, they are not very helpful.

Although libbpf and CO-RE are recent technologies, they are used by big companies like Facebook (where CO-RE was created) [5], as well as in projects for monitoring networks of Kubernetes clusters [31] and security of Linux-based containers [15].

2.7 Comparison of Tools

Reviewing what was shown in this chapter, we can compare the different tools discussed. This comparison can be seen in Table 2.1.

BCC	**bpftrace**	**perf**	**libbpf + CO-RE**
(+) Plenty of documentation	**(+)** Plenty of documentation	**(+)** Plenty of documentation	**(-)** Little documentation
(-) Needs kernel header packages	**(-)** Needs kernel header packages	**(-)** Needs kernel header packages	**(+)** Does not need kernel header packages
(-) Programs are recompiled on every run	**(-)** Can only send data to user-space through the standard output		**(-)** Kernel needs to be compiled with BTF support
			(+) Same program can be used in different versions of the kernel

Table 2.1: Comparison of tools for development of eBPF programs

Chapter 3

Exploration

This chapter will go over the exploratory part of this work, discussing experiments and analyses that were done in order to understand the functionality of eBPF and how the network stack and mac80211 subsystem in the Linux kernel work.

3.1 Analysis of the mac80211 Subsystem

The general idea for the tool that was to be developed was something that would record the activity of a network and then display the changes that happened in that network in a timeline. Alongside those events, we would have the packets that caused them, so that the user could inspect those packets. But we still needed to get to grips with eBPF because we had no prior experience with it.

3.1.1 Exploration of the Network Stack

We decided to begin by analysing the Linux source code using the Elixir Cross Referencer [14], and wrote small scripts with **bpftrace** to better understand how the many components of eBPF, like maps and probes, could be used to accomplish our objective, as well as to find the limits of this technology. An example of one of these scripts was one that calculated the time it took to send a User Datagram Protocol (UDP) network packet via the `sendto` system call until the data to be transmitted reached the network card.

We started by seeing how glibc (GNU C Library) version 2.34 called the `sendto` system call of the Linux kernel (version 5.15), and from there followed the function calls in the kernel's code until we reached the function `__netdev_start_xmit`, which sends the data to be transmitted to the appropriate network driver. This part was somewhat difficult, as most functions could diverge, and macros are used a lot. The path of functions we followed for IPv4 UDP packets can be seen in Figure 3.1.

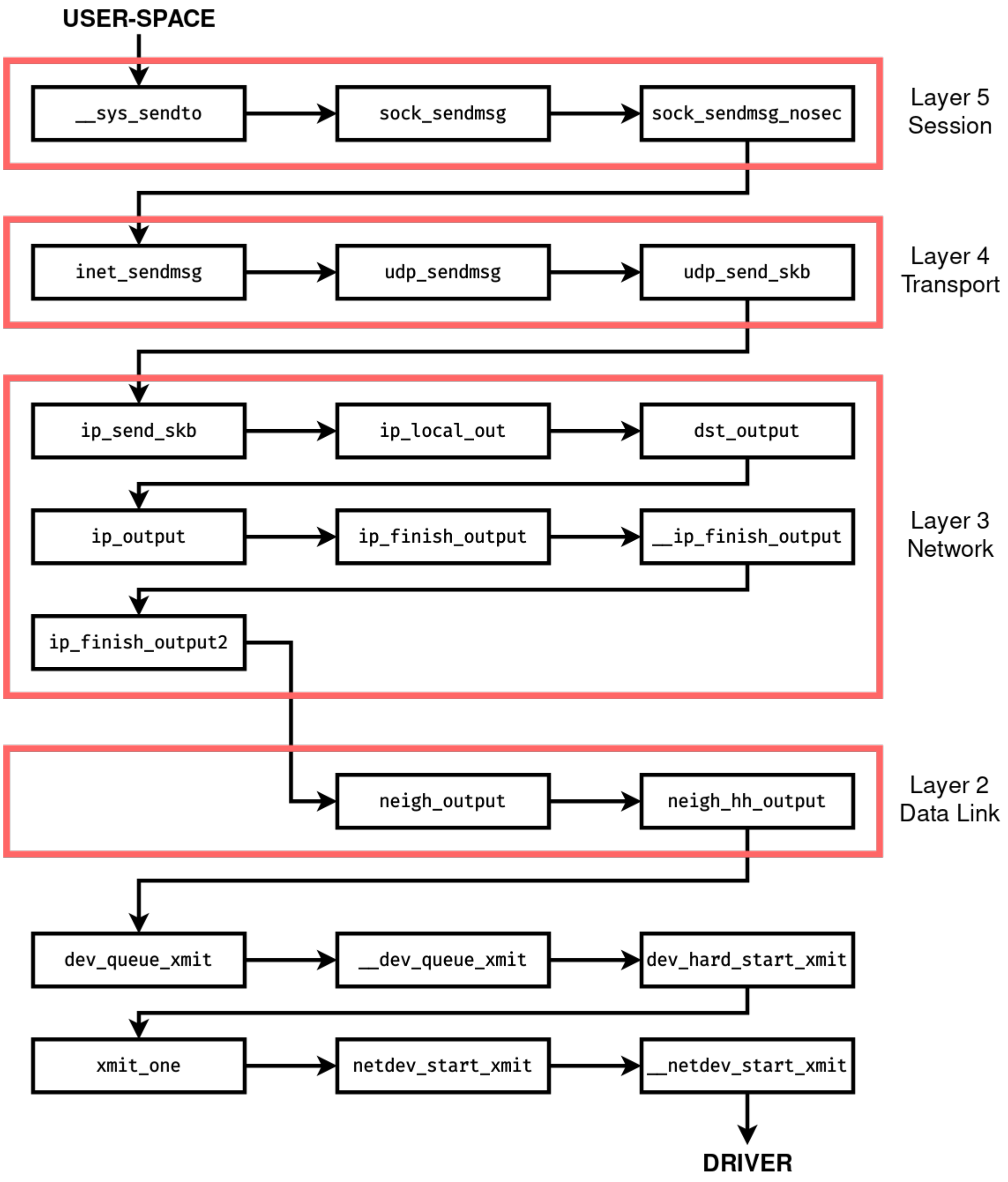


Figure 3.1: Call stack analysed for packet transmission

For the script to record the time taken, we decided to use the entry tracepoint of the `sendto` system call to save the timestamp of the call, and put a probe in `__netdev_start_xmit` to calculate the time taken. However, we ran into an error because this function is inlined, and thus can not be probed. The last function that can be probed is `dev_hard_start_xmit`, but we could also probe the exit tracepoint of the `sendto` system call. We decided to probe both the function and the exit tracepoint, for both to calculate the time. This way we would get two different times: the time it took from the system call until it reached the `dev_hard_start_xmit` function, and the time it took for the whole system call to complete. The code for this script can be seen in Listing A.1.

3.1.2 Use of Emulation

We wanted to monitor Institute of Electrical and Electronics Engineers (IEEE) 802.11s mesh networks in particular, and to perform tests we would need a mesh network. For this, we opted to go with an emulated network instead of using real hardware to save on time and to make testing simpler and more predictable (ability to remove interference, adjustable antenna range, etc.). We used mininet-wifi [16], which had everything we needed, and even included the setup for an example mesh network.

We quickly ran into an issue with mininet-wifi, however. The Linux distribution we were using was not officially supported by mininet-wifi. Thankfully, the network emulator had virtual machine images available for this type of situation, but we had some trouble with the packages in the repositories of the distribution used by the virtual machine. Not only was the version of **bpftrace** available quite old, but the package of the kernel headers provided, which were used to get structure definitions, only had the files from the **include** directory of the kernel source code, contrary to the distribution we were using, which had all header files. These issues were preventing some of our scripts from running. To solve this, we decided to try to install mininet-wifi manually in our system, despite it using a distribution that was not officially supported. Although it required some manual dependency checking and installing, the mininet-wifi installation worked without problems.

3.1.3 Finding Relevant Mesh Network Functions

Because our focus was on IEEE 802.11s mesh networks, we decided to check the content of the mac80211 subsystem. We tried to find resources that mentioned which functions were used to manipulate the system's mesh path table, but all we found were links to the source code files, which we already had. The only solution that seemed viable was to find these functions ourselves. We started by going through all the files that had "mesh" in their name in the mac80211 subsystem folder, saving the names of all of their functions. We then wrote a basic **bpftrace** script that probed all of these functions, printing their names if they were called. This way, whenever something that had to do with mesh networking happened in the kernel, we would see the names of the functions that were executed. This script was quite big, but a snippet of it can be found in Listing A.2.

With mininet-wifi up and running a simple IEEE 802.11s mesh network composed of 3 stations, we executed the script we wrote and noticed that quite a lot of functions were showing up. Analysing the content of these functions, as well as their comments (if they had any), we noticed that most of them could be ignored, as they performed actions that did not affect the mesh path table. After removing the functions that are not relevant for monitoring path changes, we ended up with two functions in our list: `mesh_path_add`, which inserts a mesh path in the mesh path table, and `mesh_path_assign_nexthop`, which changes the **nexthop** value of a given mesh path. We didn't see any paths being deleted, which was expected given that the test performed was short. However, knowing that the deletion of paths was possible, we considered `mesh_path_del` as well.

3.1.4 Choice of eBPF Framework

With these functions in mind, we started developing our program. We had to make a choice between using BPF Compiler Collection (BCC) or Compile Once - Run Everywhere (CO-RE). Although more complex and with less documentation, we decided to try CO-RE, using the libbpf-bootstrap repository available. However, we quickly hit a wall. The example in the blog posts made by the author of CO-RE mentioned that the file containing the structure and type definitions used in the kernel needed to be generated with the `bpftool` command, using the BPF Type Format (BTF) file `/sys/kernel/btf/vmlinux`. The command seemed to have worked at first, but including the generated file in our program was resulting in the error of unknown structures used. Not finding any mention of this issue anywhere, and with all the examples available using the exact the same command, we decided to switch to BCC using Python. Because the kernel headers package provided by the distribution we were using included all the header files of the Linux source code, we had no problems of unknown structures using BCC.

3.1.5 Probing Packet Transmission and Reception

The idea of our program was to retrieve the data of the mesh path that was inserted, modified, or removed from a mesh path table, by probing the functions that performed these actions when a thread executed them, store that data in a BPF map, and when that same thread passed through the tracepoint at packet transmission/reception, load the data stored in the BPF map, add the important part of the packet content to it, and send it to user-space to be processed by the user-space portion. We had already found the functions used to retrieve the details of paths that were involved in modifications performed in the mesh path table, but we still needed a way to get the content of the packets that caused these actions. Thanks to the previously mentioned test that was done at the beginning with bpftrace, we found a couple of tracepoints inside the `xmit_one` function that provided access to the `sk_buff` structure that holds the contents of packets.

For packet reception however, the task was a bit harder. We found a tracepoint that worked, but the issue was that, because we are dealing with packet reception, this tracepoint is called before any calls to functions that modify the mesh path table, and we need to delete the content that was stored in the BPF map for threads that did not change the mesh path table so as not to cause memory leaks. This issue can be visualised in the difference between Figure 3.2 and Figure 3.3, where every thread that deals with packet reception stores data in the BPF map, but only the ones that deal with mesh paths delete the content stored when it is no longer needed, leaving the contents stored by the other threads in the BPF map, with no way of deleting them.

One way to solve this issue would be to find another tracepoint or function to probe located after any change to the mesh path table, to capture all executions that also passed through the packet reception tracepoint in order to delete the content stored in the BPF map that was not used. Unfortunately, we did not find any tracepoint of function we could probe that met these requirements.

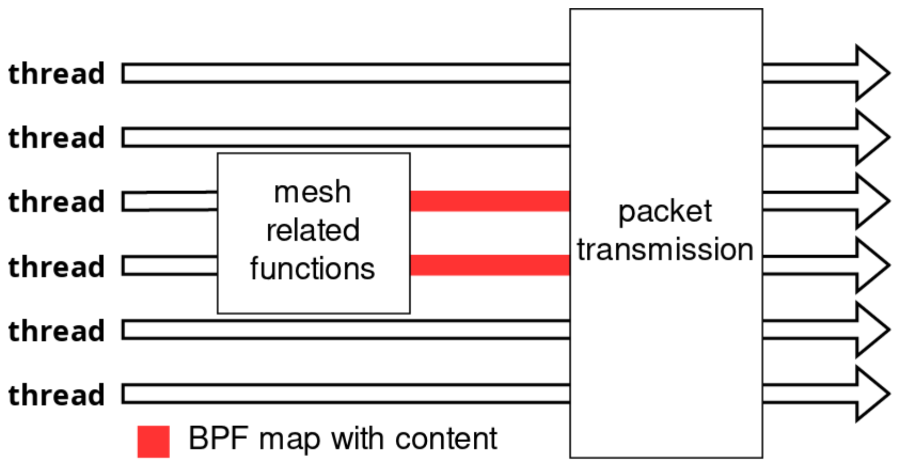


Figure 3.2: Use of BPF maps in packet transmission

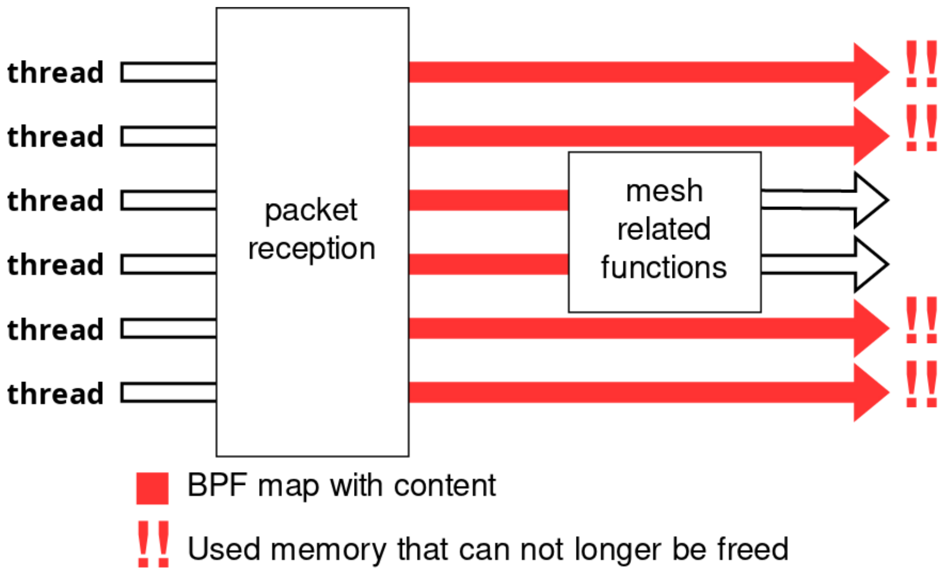


Figure 3.3: use of BPF maps in packet reception

Because of this, we had to look for an alternative. We wrote a one-line script, shown in Listing 3.1, that printed the call stack of kernel threads when they passed through `mesh_path_add`, and found that the function `ieee80211_mesh_rx_queued_mgmt` was called every time (except for when mesh paths were added by packet transmission instead of reception), and it had the `sk_buff` structure in its arguments. After checking that this function was called by a worker thread that executed `ieee80211_iface_process_skb` for every packet received, we decided to use ieee80211_mesh_rx_queued_mgmt. We would still need to use two probes, one at the function entry and another at the exit (because BCC can't get function arguments at the exit), but we could ensure that everything that was written into the BPF map would later be removed.

While looking for solutions to this problem, we also stumbled upon some tracepoints that are called on commands from user-space that affected the mesh path table, including insertion, modification, and deletion of mesh paths, through the usage of the functions ieee80211_add_mpath, ieee80211_change_mpath, and ieee80211_del_mpath respectively. Along with these tracepoints, there are also tracepoints at the exit of these actions, used to retrieve the exit value of these functions. Because these three functions all return int, we decided to add the tracepoint rdev_return_int to our program to capture actions that modify the mesh path table taken from the user-space.

```
kprobe:mesh_path_add { @[kstack] = count(); }
```

Listing 3.1: Script to print the kernel stack

3.1.6 Capturing Relevant Packets

At this point, we had the structure of the eBPF program pretty much set, but there was still one thing we wanted to improve. We had access to the packets, but we did not want to send their whole content to user-space, since we only needed the content of the data link layer. While looking around the Linux kernel, searching for how to access the fields that we would need, we found the structure ieee80211_hdr in the file include/linux/ieee80211.h, and in the same file we found some functions that led to examples of how the structure could be used, which was to cast the data field of the sk_buff as an ieee80211_hdr structure pointer.

We wrote a script that had a probe in the function mesh_path_add where it added its thread ID in an BPF map, using the thread ID as the key as well, and in the tracepoint net:net_dev_xmit, used in packet transmission, it cast the data field of the sk_buff structure as an ieee80211_hdr and printed all of its fields, if and only if the BPF map had its thread ID stored. This resulted in the script printing the link layer of packets that were being sent by threads that had inserted a mesh path to the mesh path table earlier.

Running this script, we found that all the fields were correct except for the address 1 field, which identifies the immediate receiver of the frame. Instead of the address that was shown in the corresponding packet in Wireshark, the field showed up as all zeros. After a bit of thinking, we realised that this address shows as all zeros because the system that sent this packet only knew the destination, but not the receiver, which could be the destination itself, or any other device. Because this field would cause problems when comparing with packets from the packet capture files, we decided to ignore addresses that show as all zeros.

3.1.7 Switch from BCC to CO-RE

After making sure the program worked in the emulated environment, it was time to test it with real hardware. We started with a couple of computers with different distributions (one with Arch Linux and another with Fedora) and a Raspberry Pi. However, we ran into an issue we had already faced before. Just like the distribution used by the mininet-wifi virtual machine, most distributions' kernel header packages only include the header files present in the **include** directory of the Linux source code, meaning that some of the structures we were using were not available in the Raspberry Pi, Ubuntu, Fedora, etc. We could solve this by copying the structures we needed to our program, but these structures have other structures as fields, which meant we needed to copy even more structures. Not only that, but we would also need to be cautious of Linux updates changing the contents of these structures. Another option would be to make the program depend on the Linux source code, but not all distributions provide the source code as a package, and this would also need to be updated along with the kernel itself. We ended up trying to see if we could go back to using CO-RE. After some time, we found that `vmlinux` was not the only file in the `/sys/kernel/btf/` folder. It includes plenty more files, one of them named `mac80211`. We tried generating the file with the structure and type definitions using `/sys/kernel/btf/mac80211`, and testing it, it worked without issues. As a result, we decided to switch completely to CO-RE.

We would need to switch from Python as we did not find a wrapper for it for libbpf, which is needed to use CO-RE. The languages we could use were C/C++, Rust, or Go. We didn't want to deal with manual memory management if we could, and with very little Go experience, so we decided to use Rust. Because of how CO-RE works, the eBPF portion also required some changes. One of the biggest changes was the removal of the entry probe for `ieee80211_mesh_rx_queued_mgmt`, because, unlike BCC, CO-RE can access the arguments of a function at its exit. However, because arguments can be pointers, as is the case for the argument with the packet content, the content they point to at the exit can be different from the content they pointed to at the entry. We did a few tests to check if the content of the packet changed during the execution of the function and found that it never happened. In the future, a more thorough assessment will be necessary to make sure that this is always the case. Because using a single probe at the exit would simplify the code structure, and we never saw the content of the packet change, we decided to remove the probe at the beginning. The other main change was the switch from probing `mesh_path_del` to `__mesh_path_del`. We did this because we were unable to retrieve the destination field of the path from the arguments of `mesh_path_del`. We believe CO-RE is capable of this, but none of the examples provided helped in finding a solution. When modifying the probe, we noticed that `__mesh_path_del` was called from other parts of the code as well, not just `mesh_path_del`, so we added a few more probes to take those calls into consideration. These are explained in detail in Subsection 4.1.1.

With these changes in place, the program started working on all the distributions we were testing, but it still was not working in the Raspberry Pi. Using the command `zgrep BTF /proc/config.gz`, we found that the kernel being used in the Raspberry Pi was not built with BTF support. Most distributions build the kernel with this support for the x86 architecture, but none of the distributions we tried for the Raspberry Pi offered the kernel with BTF support compiled in, so we tried to compile the kernel ourselves. Unfortunately, that also failed without us understanding why. To prevent this issue from blocking our progress, we decided to continue the development leaving the Raspberry Pi aside for a later date.

3.2 Event Capture and Packet Association

As the main objective of the program was to show the user details about paths that were added, modified, or removed from a system's mesh path table, along with the respective packet that caused that action, we had to obtain this information somehow.

Getting the details of paths was the easy part. As mentioned above, we probed the functions that modified the mesh path table, and since they have a pointer to the path structure in their arguments (except for `mesh_path_add` which has other structures), we could take the information directly and store it in a BPF map to send it to the user-space later.

The work required to get the packet content was somewhat more involved. In the tests that we performed earlier, we noticed that whenever the mesh path table was modified, functions related to packet transmission or reception were executed, which meant that we could get the packet that caused the action by following the thread's path. We set the probe and tracepoint used for packet reception and transmission respectively mentioned earlier, and used the thread's ID to check if a thread that was receiving/transmitting a packet had passed through a function that modified the mesh path table earlier, and, if it did, use that packet's content. Instead of sending the whole packet to the user-space, we used a structure called `ieee80211_hdr` to get just the elements we needed in order to be able to unambiguously identify the packet. We do this to keep the memory usage as low as possible and to minimise the overhead of our eBPF programs. The fields we take from the packet are the **Frame Control**, **Sequence Control**, and **QoS Control** (when available) fields, as well as the three (four in some cases) MAC addresses. We use the **Frame Control** to check the size of the data link layer, as well as to check if the **QoS Control** field is included and if there are three or four addresses. The **Sequence Control** is used to differentiate packets that have all the other fields equal. According to section 10.3.2.14 of the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard [20], only the first two addresses of the MAC layer are needed to identify packets, along with the **QoS Control** field, when it is present. Because we already had the **Frame Control**, we thought we might as well use it for packet comparison as well. We ended up not using the third and fourth addresses, but kept them as well in case they would be needed in the future.

Chapter 4

Development

This chapter will cover the architecture of the tool that was developed to realise the objective of this thesis. This tool captures the paths that were created, modified, and deleted in an IEEE 802.11s mesh network, and associates them with the packets that caused these events.

The tool consists of two programs: a program that captures the events and saves them in output files, which will be referred to as **service**, and a program to view the captured events of several computers side-by-side, referred to as **central**. The way this tool is meant to be used is summarised in Figure 4.1.

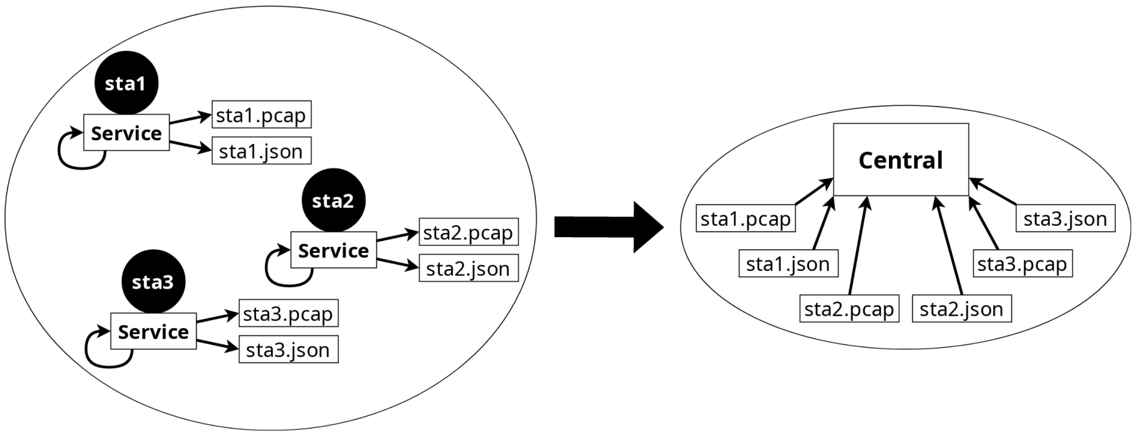


Figure 4.1: Usage of the tool developed

4.1 Architecture of the Service

The **service** program can be divided into two parts. The eBPF part that runs in the kernel-space and captures the events related to alterations in the mesh path table, sending their details to user-space, and the Rust part that runs in the user-space, receiving the data sent by the eBPF portion of the code, while also capturing network packets at the same time using **libpcap** in order to associate packets to the actions performed in the system's mesh path table.

The **service** captures the events that alter the mesh path table and network packets at the same time, saving them to output files, and when the user sends a signal to stop, the program stops these captures. It starts by creating the output files, a JSON file that stores a list of events and a network capture file that stores packets, and then loads the eBPF code. Then, a new thread is created whose sole purpose is to capture network packets. This new thread keeps capturing packets and storing them in the appropriate output file in a loop that only stops when the program receives a termination signal (one of `SIGTERM`, `SIGQUIT`, or `SIGINT`).

Immediately after creating the packet capturing thread, the main thread goes into a loop of its own doing the same thing, but instead of capturing packets, it captures events sent by the eBPF code. This loop uses the same conditional variable used by the packet capturing thread, so when one of the threads receives a termination signal, both exit their respective loops.

After receiving a termination signal and leaving their loops, the packet capturing thread stops, and the main thread continues. It then reads the contents of both output files, creating a list of events and an iterator over packets. The reason the program creates the output files at the start and writes to them immediately, instead of creating these structures first and writing them to the output files at the end, is to prevent the loss of data in case of a crash, as well as to limit the memory usage of the program when it is run for a long period of time.

With these two structures, the program goes over all the packets and events, and checks which packets resulted in which events, storing this information in the events themselves (this process is explained in more detail in Subsection 4.1.2). Afterwards, it rewrites the output file for the captured events with the newly modified events (including the packets each event is related to), and terminates.

4.1.1 eBPF Module

The eBPF portion of the code is composed of nine probes. There are three probes that detect if an alteration is made to the mesh path table, three to detect the source of the action (if it was a packet reception or transmission that caused the change in the mesh path table, or if it came from a command from user-space), two for when a path is removed because it expired, and the last one is for a special case which we will discuss later.

The three probes used to detect alterations in the mesh path table are in the functions `mesh_path_add`, `mesh_path_assign_nexthop`, and `__mesh_path_del`, the first two having been discussed in Subsection 3.1.3 and the last one in Subsection 3.1.7. These are used to gather information about the mesh path involved, including its destination, nexthop, as well as the timestamp of the event and the MAC address and name of the interface. The probe for `mesh_path_add` is the simplest, as it only stores the information about the path that was added in a BPF map. In another BPF map, the probe stores a value (which will be referred to as the **situation** value) that indicates that the information stored in the first BPF map came from a path addition to the mesh path table. Figure 4.2 shows in detail how this and the following probes use these maps. The probe for mesh_path_assign_nexthop is a bit more complex, as this function is used both when a new path is added, and when an existing path is altered, meaning that mesh_path_add can be called before it. Because of this, this probe checks if there is a **situation** value already present for the running thread in the BPF map, changing it to a new value indicating if the situation is a new path being added or if it is an existing path being modified. The information about the path is stored in the appropriate BPF map if necessary. The relationship between these two probes can be seen in Figure 4.3. The last probe, in __mesh_path_del, detects the removal of paths from the mesh path table, and if we ignore the possibility of paths being expired, it works just like the probe for mesh_path_add. The case of a path being expired will be explained shortly.

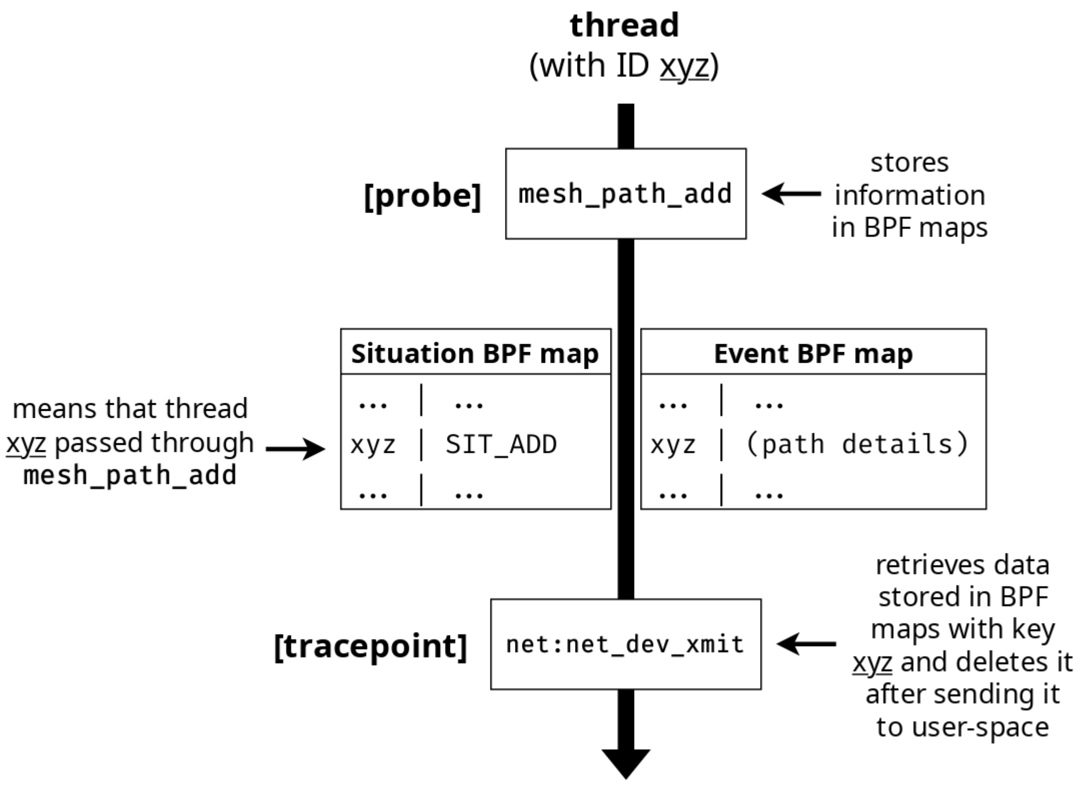

thread
(with ID xyz)
[probe]
mesh_path_add
stores information in BPF maps
Situation BPF map
... | ...
xyz | SIT_ADD
... | ...
Event BPF map
... | ...
xyz | (path details)
... | ...
means that thread xyz passed through mesh_path_add
[tracepoint]
net:net_dev_xmit
retrieves data stored in BPF maps with key xyz and deletes it after sending it to user-space

Figure 4.2: Detail of BPF maps usage

For the next three probes, which are talked about in Subsection 3.1.5, two are located in the tracepoints net:net_dev_xmit (packet transmission), and rdev_return_int (command from user-space), and the third one is in the function ieee80211_mesh_rx_queued_mgmt (packet reception). These probes all work the same way. They take whatever is in the BPF maps, and with the aid of the **situation** value, set the event's correct **reason** field (which specifies the action taken on the mesh path table and its source) and send the event to user-space to be received by the Rust portion of the code, including the content of the link layer of the packet that caused the event, if applicable.

There are also two probes at the entry and exit of the function mesh_path_expire. The entry probe sets the situation value in the proper BPF map, so that the probe at

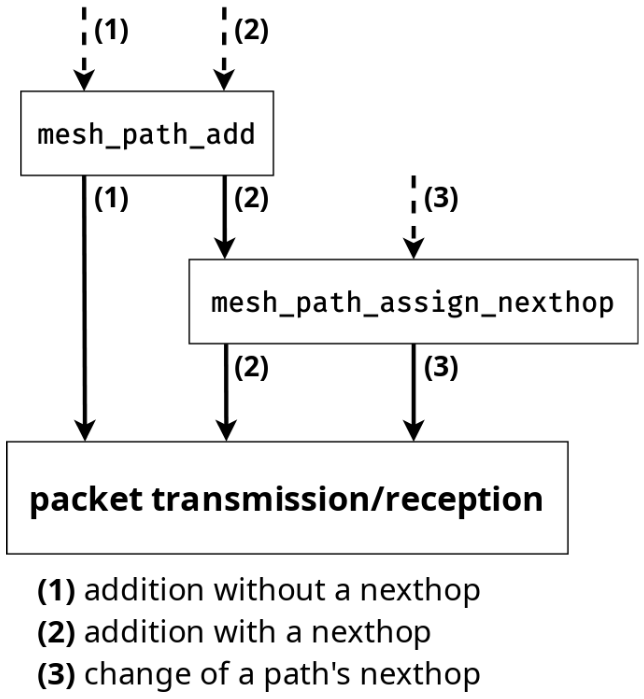

(1)
(2)
mesh_path_add
(1)
(2)
(3)
mesh_path_assign_nexthop
(2)
(3)
packet transmission/reception
(1) addition without a nexthop
(2) addition with a nexthop
(3) change of a path's nexthop

Figure 4.3: Probes for insertion and modification

__mesh_path_del sends the event information directly to the user-space, while the exit probe simply removes the data from the BPF maps, as it is not needed any more. The reason to use two probes this way instead of having a single probe sending the data to user-space directly (like the other three previously discussed), is because mesh_path_expire calls __mesh_path_del more than once. Since only one event can be stored at a time per thread (because the threads' IDs are being used as the keys in the BPF maps, and BPF maps do not allow the usage of arrays of structures), only the information about the last path being deleted would be sent to user-space instead of all paths. The way these probes interact is demonstrated in Figure 4.4.

Finally, there is also a probe in mesh_plink_deactivate, which is a function that calls __mesh_path_del indirectly. This probe is used to ignore any calls to this function. The reason for this is that we were not able to determine all the possible reasons for this function being called. Packet transmission and reception would be captured, but some actions could be missed. For example, we found that this function could be called by ieee80211_sta_expire, and to capture this we would need more probes, just like how probes for mesh_path_expire were required. Because we found many functions calling mesh_plink_deactivate, and any of them could end up requiring more probes, the time it would take to analyse all the different possibilities would be too much, so we decided to ignore calls to this function.

4.1.2 Packet and Event Relation

The packet/event relation section of the code, whose purpose is to identify which packet caused each event, as seen in Figure 4.5, is composed of two loops, one inside the other. The program

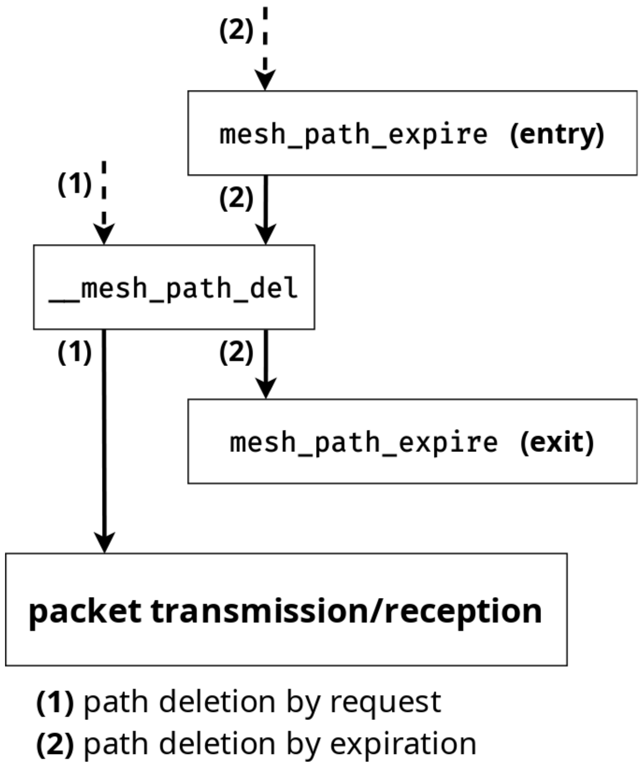

(2)
mesh_path_expire (entry)
(1)
(2)
__mesh_path_del
(1)
(2)
mesh_path_expire (exit)
packet transmission/reception
(1) path deletion by request
(2) path deletion by expiration

Figure 4.4: Probes for deletion and expiration

goes over every packet individually, and for each one, it goes over every event that was captured. Even if an event gets matched with a packet, the next packets will still check all events, including the ones that matched with other packets earlier. This $O(n^2)$ algorithm is used, as opposed to a more efficient one that would remove events as they are matched, because of an issue that prevents us from obtaining the full content of a packet in some events, where we have to ignore the missing content, which can lead to an event matching more than one packet.

Because at the time of development a Rust library to access fields of network packets did not exist, the program checks the raw data of the packets for the fields manually in the array of bytes provided. It starts by making sure that there are enough bytes to get all the data needed to compare with the details of the event, and, if there are, compares the frame control, sequence control, and, if applicable, Quality of Service (QoS) control fields, as well as the address 1 and address 2 fields. As mentioned in Section 3.1, we noticed that in some events the address 1 field obtained from the kernel-space was incorrect, it being the address `00:00:00:00:00:00` instead of the expected value because the computer that sends the packet does not know the Media Access Control (MAC) address of the receiver. We decided to ignore this field when it takes the aforementioned value. We did not see this happen with the address 2 field, but do the same for precaution.

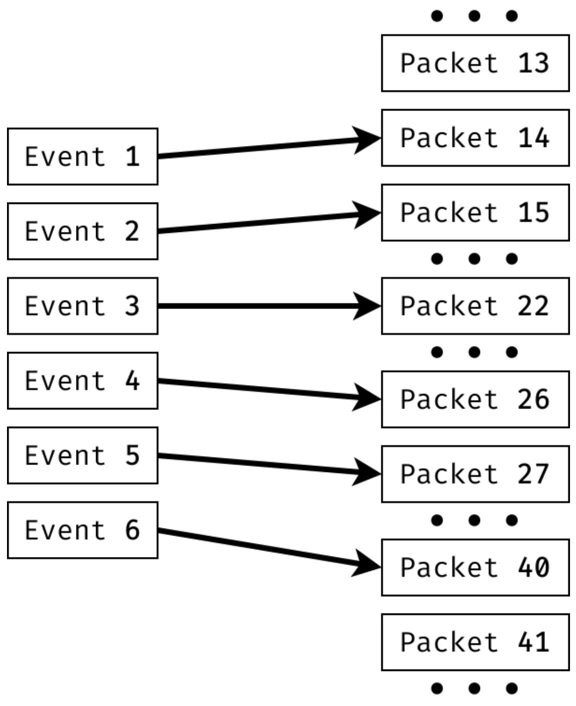


Figure 4.5: Relation of packets and events

4.2 Architecture of the Central

The **central** is a much simpler program than the **service**, as its only goal is to display the events captured in a group of computers in a more human-friendly way. Most of its code is for the Graphical User Interface (GUI) logic.

The program takes a folder with the output files generated by the **service** as an argument, and checks the file names, accepting only files that end in `.json` and `.pcap`. For each pair of files that contains the same stem, a structure called `Station` is created, containing the list of events in the events file, and the name of the packet capture file. After checking all files, a list of several `Station` instances is returned.

The last step before displaying the events is to sort them in chronological order. This is done by increasing the size of the list of events for each station to have the capacity for all events in all the stations. Then, using their timestamps, the events are ordered in such a way that, for each place in the stations' lists, where one station has an event, all the others have an empty element. This can be visualised in Figure 4.6. Although not very efficient, it is the simplest method we could come up with to implement.

Finally, the GUI is created, where the user can view all the events of all the stations side by side, and not only inspect the details of each event, but also see the packets that caused those events in Wireshark with the press of a button. Figure 4.7 displays an example capture.

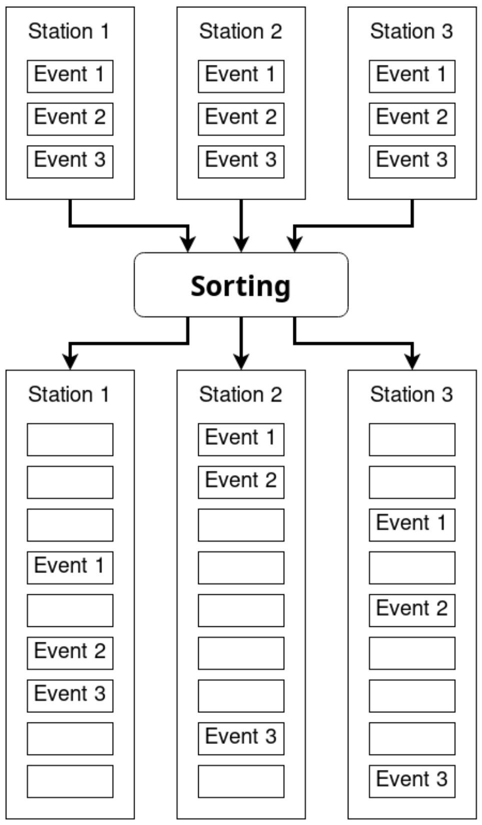
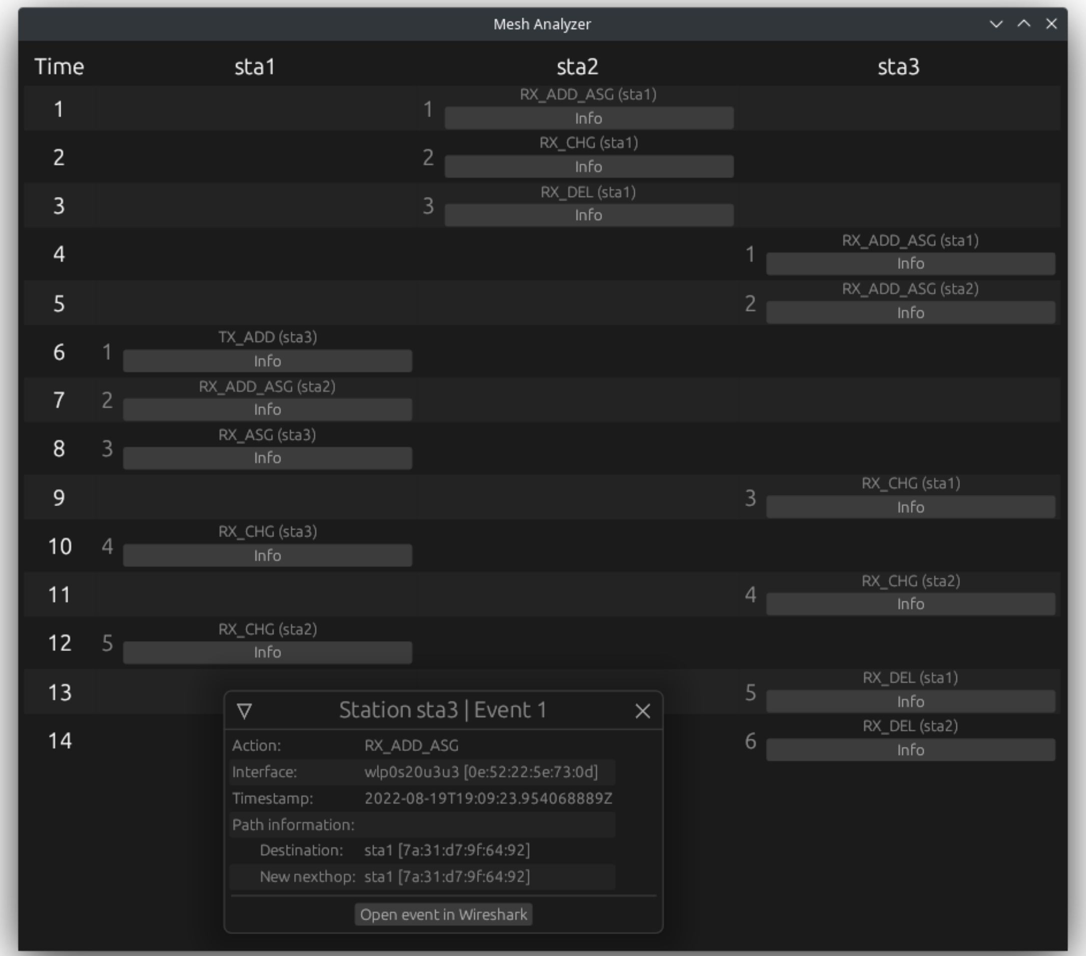


Figure 4.6: Chronological sorting of events



Mesh Analyzer

Time	sta1	sta2	sta3
1		1 RX_ADD_ASG (sta1) Info	
2		2 RX_CHG (sta1) Info	
3		3 RX_DEL (sta1) Info	
4			1 RX_ADD_ASG (sta1) Info
5			2 RX_ADD_ASG (sta2) Info
6	1 TX_ADD (sta3) Info		
7	2 RX_ADD_ASG (sta2) Info		
8	3 RX_ASG (sta3) Info		
9			3 RX_CHG (sta1) Info
10	4 RX_CHG (sta3) Info		
11			4 RX_CHG (sta2) Info
12	5 RX_CHG (sta2) Info		
13			5 RX_DEL (sta1) Info
14			6 RX_DEL (sta2) Info

Station sta3 | Event 1

Action:	RX_ADD_ASG
Interface:	wlp0s20u3u3 [0e:52:22:5e:73:0d]
Timestamp:	2022-08-19T19:09:23.954068889Z
Path information:	
Destination:	sta1 [7a:31:d7:9f:64:92]
New nexthop:	sta1 [7a:31:d7:9f:64:92]

Open event in Wireshark

Figure 4.7: GUI interface

Chapter 5

Tests and Validation

Some of the tests made during the exploration have already been mentioned in Chapter 3, but here we will go over a couple of tests in detail that were important in the development of our tool and verifying that it worked as expected.

5.1 Validation in Emulated Environment

After developing the initial version of the full service program, one of the tests we performed using mininet-wifi consisted of three stations (named sta1 sta2 and sta3), where sta1 and sta3 were too far apart from each other to communicate directly, but both in range of sta2, as shown in Figure 5.1, and all of them without any paths in their mesh path tables initially, pinging sta3 from sta1. The host system used the Arch Linux distribution, running the Long-Term Support (LTS) version 5.10 Linux kernel.

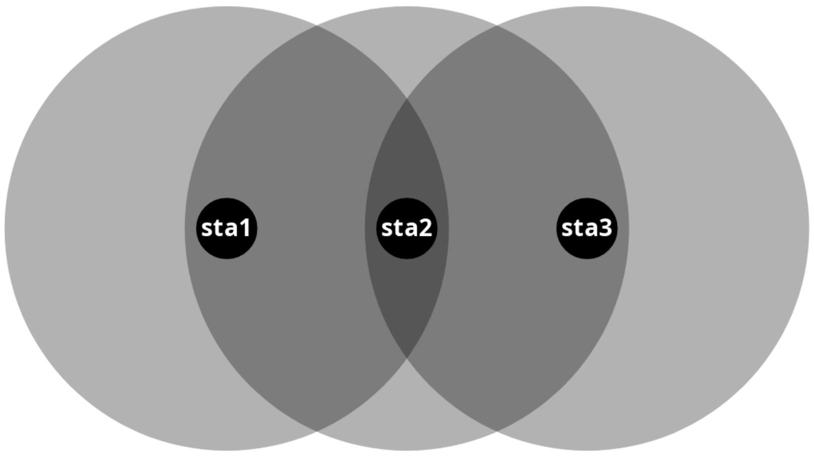
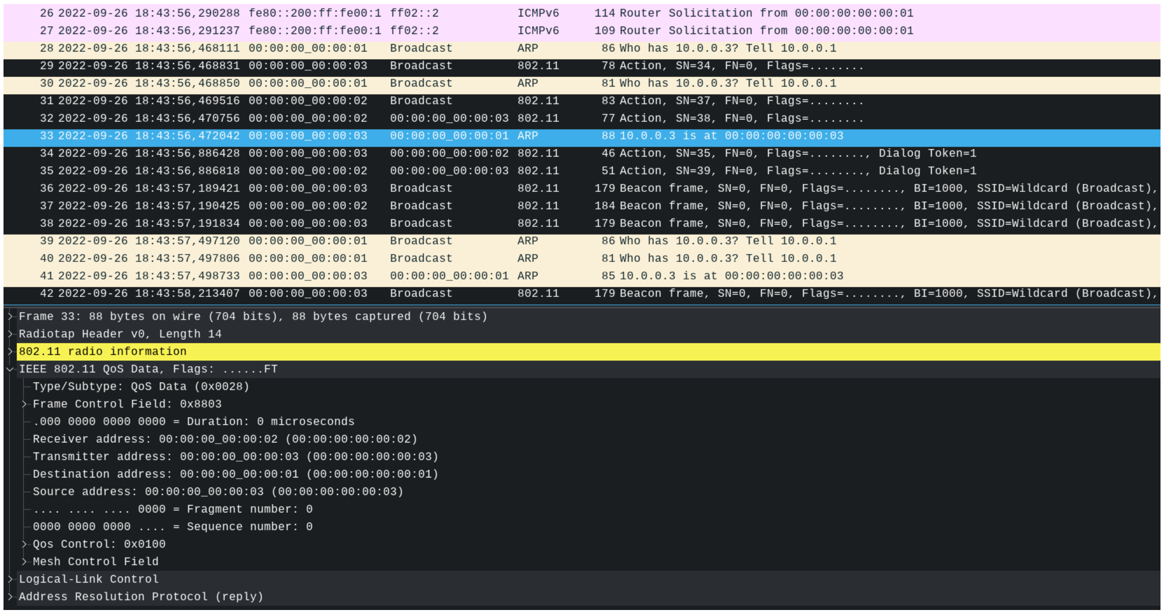


Figure 5.1: Test configuration used in mininet-wifi

We found that the first station to create and add a mesh path was sta3. Although sta1 was the one that pinged sta3, it could not create a path yet because it did not know the Media Access

Control (MAC) address of sta3. So sta1 only sends an Address Resolution Protocol (ARP) request in broadcast, which is then retransmitted by sta2, and after sta3 receives it, it creates a path for sta1 (without the nexthop field filled in) when it sends its ARP response, highlighted in blue in Figure 5.2, which shows the packet capture that was executed in sta3.



```
26 2022-09-26 18:43:56,290288 fe80::200:ff:fe00:1 ff02::2           ICMPv6     114 Router Solicitation from 00:00:00:00:00:01
27 2022-09-26 18:43:56,291237 fe80::200:ff:fe00:1 ff02::2           ICMPv6     109 Router Solicitation from 00:00:00:00:00:01
28 2022-09-26 18:43:56,468111 00:00:00_00:00:01   Broadcast         ARP         86 Who has 10.0.0.3? Tell 10.0.0.1
29 2022-09-26 18:43:56,468831 00:00:00_00:00:03   Broadcast         802.11      78 Action, SN=34, FN=0, Flags=........
30 2022-09-26 18:43:56,468850 00:00:00_00:00:01   Broadcast         ARP         81 Who has 10.0.0.3? Tell 10.0.0.1
31 2022-09-26 18:43:56,469516 00:00:00_00:00:02   Broadcast         802.11      83 Action, SN=37, FN=0, Flags=........
32 2022-09-26 18:43:56,470756 00:00:00_00:00:02   00:00:00_00:00:03 802.11      77 Action, SN=38, FN=0, Flags=........
33 2022-09-26 18:43:56,472042 00:00:00_00:00:03   00:00:00_00:00:01 ARP         88 10.0.0.3 is at 00:00:00:00:00:03
34 2022-09-26 18:43:56,886428 00:00:00_00:00:03   00:00:00_00:00:02 802.11      46 Action, SN=35, FN=0, Flags=........, Dialog Token=1
35 2022-09-26 18:43:56,886818 00:00:00_00:00:02   00:00:00_00:00:03 802.11      51 Action, SN=39, FN=0, Flags=........, Dialog Token=1
36 2022-09-26 18:43:57,189421 00:00:00_00:00:03   Broadcast         802.11     179 Beacon frame, SN=0, FN=0, Flags=........, BI=1000, SSID=Wildcard (Broadcast),
37 2022-09-26 18:43:57,190425 00:00:00_00:00:02   Broadcast         802.11     184 Beacon frame, SN=0, FN=0, Flags=........, BI=1000, SSID=Wildcard (Broadcast),
38 2022-09-26 18:43:57,191834 00:00:00_00:00:03   Broadcast         802.11     179 Beacon frame, SN=0, FN=0, Flags=........, BI=1000, SSID=Wildcard (Broadcast),
39 2022-09-26 18:43:57,497120 00:00:00_00:00:01   Broadcast         ARP         86 Who has 10.0.0.3? Tell 10.0.0.1
40 2022-09-26 18:43:57,497806 00:00:00_00:00:01   Broadcast         ARP         81 Who has 10.0.0.3? Tell 10.0.0.1
41 2022-09-26 18:43:57,498733 00:00:00_00:00:03   00:00:00_00:00:01 ARP         85 10.0.0.3 is at 00:00:00:00:00:03
42 2022-09-26 18:43:58,213407 00:00:00_00:00:03   Broadcast         802.11     179 Beacon frame, SN=0, FN=0, Flags=........, BI=1000, SSID=Wildcard (Broadcast),
> Frame 33: 88 bytes on wire (704 bits), 88 bytes captured (704 bits)
> Radiotap Header v0, Length 14
> 802.11 radio information
v IEEE 802.11 QoS Data, Flags: ......FT
    Type/Subtype: QoS Data (0x0028)
  > Frame Control Field: 0x8803
    .000 0000 0000 0000 = Duration: 0 microseconds
    Receiver address: 00:00:00_00:00:02 (00:00:00:00:00:02)
    Transmitter address: 00:00:00_00:00:03 (00:00:00:00:00:03)
    Destination address: 00:00:00_00:00:01 (00:00:00:00:00:01)
    Source address: 00:00:00_00:00:03 (00:00:00:00:00:03)
    .... .... .... 0000 = Fragment number: 0
    0000 0000 0000 .... = Sequence number: 0
  > Qos Control: 0x0100
  > Mesh Control Field
> Logical-Link Control
> Address Resolution Protocol (reply)
```

Figure 5.2: ARP response that caused a path to be added to the mesh path table

Immediately after, sta2 creates a path to sta3 and retransmits the ARP response to sta1, which in turn receives the MAC address of sta3 through sta2, and creates its mesh paths, both for sta2 and sta3.

5.2 Validation with Hardware Nodes

Because we spent most of our time in development testing with mininet-wifi, we were only able to do a simple test with real hardware, using two computers running Arch Linux, just like the host system used in the tests in the emulated environment (one using the `rtl8723be` driver for the wireless network controller and the other using `iwlwifi`), and a third computer running Fedora 36 with version 5.17 of the Linux kernel, also using the `iwlwifi` driver. We tried to replicate the test mentioned in the previous section, placing sta1 and sta3 far away from each other in the hopes that sta2 would be needed for the other two stations to communicate, but the space we had was not enough, as can be seen in the results displayed in Figure 4.7, which shows at the bottom details about the first event captured in sta3, where a path was added with the destination and the nexthop both set to sta1's Media Access Control (MAC) address, meaning sta2 was not used for communication between the two stations. Still, we can verify that the tool we developed worked as expected, showing a mesh path being created and then deleted in sta2 (most likely because it ended up not being used), and sta3 and sta1 creating mesh paths and settings their **nexthops** values.

We did notice some unexpected behaviour. For example, in event number 10, sta1 changed the **nexthop** field of its path to sta3 to the value it already had previously, effectively not changing anything. The reason for this behaviour was most likely a change to the path's sequence number, which is a field we do not capture, but is maintained in the mesh path table entries.

Chapter 6

Conclusion

Recalling what was said in Chapter 1, the objectives of this thesis were to explore how eBPF could be used for monitoring experiments in wireless networks, and to create a program that would showcase this.

This work was very exploratory, as it was necessary to examine the code of the Linux kernel which is not only very extensive but also very complex, study Institute of Electrical and Electronics Engineers (IEEE) 802.11s mesh networks, as well as learn eBPF, all of which are fields where we had little to no prior experience, in order to develop a tool that took advantage of eBPF to monitor these networks. Most of the documentation of eBPF and the tools and frameworks around it assume some familiarity with the Linux source code, how it works, and its most used structures, which was not the case for us.

As for the programs developed, we accomplished our objective, which was to create a tool that could demonstrate how eBPF could be used in experiments of wireless networks. Our service program can detect changes in the mesh path table of several systems, and its output files can be then used in conjunction with outputs from other systems to be analysed with the central program to get a timeline of the activity in an entire IEEE 802.11s mesh network. The tool developed can be found at https://github.com/PillTime/mesh_analyzer.

It is worth mentioning that in our program we use probes as a necessity, which are not as stable as tracepoints. This means that an update to the kernel that changes the functions we probe could result in our program not working correctly, and an update to fix these probes would be required.

6.1 Future Work

Although we were able to reach our objectives, we believe our programs could be improved with more features and fixes to compromises that had to be made due to the lack of time available. The following paragraphs contain some ideas and possible solutions for the implementation.

The first one is the presence of the probe in the function `mesh_plink_deactivate`. This probe ignores some actions that can modify the mesh path table, so removing it would be an improvement. To remove it, a deeper analysis of the functions that call `mesh_plink_deactivate` would be needed, to take into account all the possible call stacks.

One of the biggest issues we wanted to fix but could not for lack of time was the way we sort all the events in the **central** program. We use the timestamp captured along with the path information for sorting events, but since the clocks of the several computers in a network being monitored will not be perfectly synchronised, it is not a reliable metric. One way we think this could be solved would be to use the ordering of packets instead, using two packet capture files where one has a packet that causes a change to a mesh path table being sent, and another has that same packet being received, and using that packet as a basis for sorting events between the two stations where these packets were captured. The timestamp of the events could additionally be used to shift the events in a station that were not caused by a packet in relation to the events in other stations, using the packet previously mentioned as a reference point in time.

With hindsight, we can see that the decision to switch to a single probe at packet reception when we switched from BPF Compiler Collection (BCC) Compile Once - Run Everywhere (CO-RE) was not ideal. We did it mostly because the code became shorter and much easier to comprehend. Still, although we never detected it, there is a chance that some function could change the content of a packet. If we had time we would revert to two probes, with the entry probe inserting the important content of the packet to the BPF map, have the probes at each action retrieve the information from the BPF map and submitting it to user-space, and have the exit probe delete anything in the BPF map for the cases where the thread did not alter the mesh path table.

Something that we think would be fun, but also help visualise bigger networks, is to create a graph showing the mesh paths in each event. This would basically be an easy-to-interpret timeline of the network. Being able to click on each station to see the events that it captured, as well as each mesh path to see its information, along with which packet (if applicable) caused it would be great as well. Because the events already store the source, nexthop, and destination of each path, this would only require updating the central program.

Another thing that would possibly help with bigger networks is a file that contains the information of a whole network. Right now, the **central** program takes the files of all the stations and sorts their events every time it is executed. We never experienced a slow sorting process, with the program always being opened almost immediately, but considering that our tests were always quite short and involved at most three stations, it is possible that bigger networks and longer tests would cause a slow-down. We think the **central** program could have a flag that generates a file that contains all the events of all stations already sorted, to be used in other runs, instead of the original files.

Something that would be nice to have would be a way for the central program to be able to retrieve the information gathered by the different nodes being monitored automatically, instead of relying on manual file transfers from those nodes.

The way we sort the events in the **central** program, although simple, is not very efficient given that it increases the lists of events for each station, filling them mostly with empty elements, which still occupy as much space in memory as the structures for events. An approach that would use an algorithm that sorts these events without creating empty structures would be preferable.

Something that could be improved is the fields of paths that the tool captures. Currently, it captures only the destination and nexthop of paths, but other fields can be captured, such as the metric value and the sequence number, as was noted in the last paragraph of Section 5.2.

One last thing that we think would help with analysis would be to show the time between events. This would enable users to easily determine how much time has passed between events, and could be implemented using the timestamps available in the events.

Bibliography

[1] *[PATCH net-next] extended BPF*. en. https://lkml.org/lkml/2013/9/30/627, visited 2022-09-27. Sept. 2013 (cit. on p. 6).

[2] *A thorough introduction to eBPF*. en. https://lwn.net/Articles/740157/, visited 2022-09-27 (cit. on p. 6).

[3] S. M. S. Bari, F. Anwar and M. H. Masud. 'Performance study of hybrid Wireless Mesh Protocol (HWMP) for IEEE 802.11s WLAN mesh networks'. In: *2012 International Conference on Computer and Communication Engineering (ICCCE)*. Kuala Lumpur, Malaysia: IEEE, July 2012, pp. 712–716. ISBN: 978-1-4673-0477-1. DOI: 10.1109/ICCCE.2012.6271309 (cit. on p. 4).

[4] *BPF binaries: BTF, CO-RE, and the future of BPF perf tools*. en. https://brendangregg.com/blog/2020-11-04/bpf-co-re-btf-libbpf.html, visited 2022-09-27 (cit. on pp. 7–8).

[5] *BPF CO-RE*. en. http://vger.kernel.org/bpfconf2019_talks/bpf-core.pdf, visited 2022-09-27 (cit. on pp. 8–9).

[6] *BPF CO-RE (Compile Once – Run Everywhere)*. en. https://nakryiko.com/posts/bpf-portability-and-co-re/, visited 2022-09-27 (cit. on p. 8).

[7] *BPF CO-RE reference guide*. en. https://nakryiko.com/posts/bpf-core-reference-guide/, visited 2022-09-27 (cit. on p. 8).

[8] *BPF Compiler Collection (BCC)*. en. https://github.com/iovisor/bcc/blob/master/README.md, visited 2022-09-27 (cit. on p. 7).

[9] *BPF ring buffer*. en. https://nakryiko.com/posts/bpf-ringbuf/, visited 2022-09-27 (cit. on p. 8).

[10] *bpf: increase complexity limit and maximum program size*. en. https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=c04c0d2b968ac45d6ef020316808ef6c82325a82, visited 2022-09-27. Apr. 2019 (cit. on p. 6).

[11] *bpftrace*. en. https://github.com/iovisor/bpftrace/blob/master/README.md, visited 2022-09-27 (cit. on p. 7).

[12] *Building BPF applications with libbpf-bootstrap*. en. https://nakryiko.com/posts/libbpf-bootstrap/, visited 2022-09-27 (cit. on p. 8).

[13] *eBPF Documentation*. en. https://ebpf.io/what-is-ebpf, visited 2022-09-27 (cit. on p. 6).

[14] *Elixir Cross Referencer*. en. https://elixir.bootlin.com/linux/v5.15.10/source, visited 2022-09-27 (cit. on p. 11).

[15] William Findlay, David Barrera and Anil Somayaji. *BPFContain: Fixing the Soft Underbelly of Container Security*. arXiv:2102.06972 [cs]. Feb. 2021 (cit. on p. 9).

[16] Ramon R. Fontes et al. 'Mininet-WiFi: Emulating software-defined wireless networks'. In: *2015 11th International Conference on Network and Service Management (CNSM)*. Barcelona, Spain: IEEE, Nov. 2015, pp. 384–389. ISBN: 978-3-901882-77-7. DOI: 10.1109/CNSM.2015.7367387 (cit. on p. 13).

[17] Brendan Gregg. *Bpf performance tools: Linux system and application observability*. 1st ed. Hoboken: Pearson Education, Inc, 2019. ISBN: 978-0-13-655482-0 (cit. on p. 7).

[18] M. Guesmia, M. Guezouri and N. Mbarek. 'Performance evaluation of the HWMP proactive tree mode for IEEE 802.11s based Wireless Mesh Networks'. In: *Third International Conference on Communications and Networking*. Hammamet, Tunisia: IEEE, Mar. 2012, pp. 1–7. ISBN: 978-1-4673-1006-2. DOI: 10.1109/ComNet.2012.6217743 (cit. on p. 4).

[19] *IEEE 802.11s*. en. https://wireless.wiki.kernel.org/en/developers/Documentation/ieee80211/802.11s, visited 2022-09-27 (cit. on p. 4).

[20] *IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks–Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. Tech. rep. ISBN: 9781504472838. IEEE. DOI: 10.1109/IEEESTD.2021.9363693 (cit. on pp. 3, 18).

[21] *libbpf*. en. https://github.com/libbpf/libbpf/blob/master/README.md, visited 2022-09-27 (cit. on p. 8).

[22] *Libbpf: A Beginners Guide*. en. https://www.containiq.com/post/libbpf, visited 2022-09-27 (cit. on pp. 7–8).

[23] Steven McCanne and Van Jacobson. 'The BSD Packet Filter: A New Architecture for User-Level Packet Capture'. In: *Proceedings of the USENIX Winter 1993 Conference Proceedings on USENIX Winter 1993 Conference Proceedings*. USENIX'93. San Diego, California: USENIX Association, 1993, p. 2 (cit. on p. 5).

[24] *perf Examples*. en. https://www.brendangregg.com/perf.html, visited 2022-09-27 (cit. on p. 8).

[25] *Perf Wiki*. en. https://perf.wiki.kernel.org/index.php/Main_Page, visited 2022-09-27 (cit. on p. 8).

[26] C. Perkins, E. Belding-Royer and S. Das. *Ad hoc On-Demand Distance Vector (AODV) Routing*. en. Tech. rep. RFC3561. RFC Editor, July 2003, RFC3561. DOI: 10.17487/rfc3561 (cit. on p. 4).

[27] Mihail L. Sichitiu. 'Wireless mesh networks: Opportunities and challenges'. In: *Proceedings of World Wireless Congress*. 2005 (cit. on p. 3).

[28] Yuuki Tsubouchi, Masahiro Furukawa and Ryosuke Matsumoto. 'Low Overhead TCP/UDP Socket-based Tracing for Discovering Network Services Dependencies'. en. In: *Journal of Information Processing* 30.0 (2022), pp. 260–268. ISSN: 1882-6652. DOI: 10.2197/ipsjjip.30.260 (cit. on p. 7).

[29] Marcos A. M. Vieira et al. 'Fast Packet Processing with eBPF and XDP: Concepts, Code, Challenges, and Applications'. en. In: *ACM Computing Surveys* 53.1 (Jan. 2021), pp. 1–36. ISSN: 0360-0300, 1557-7341. DOI: 10.1145/3371038 (cit. on p. 6).

[30] *Why We Switched from BCC to libbpf for Linux BPF Performance Analysis*. en. https://www.pingcap.com/blog/why-we-switched-from-bcc-to-libbpf-for-linux-bpf-performance-analysis/, visited 2022-09-27 (cit. on p. 7).

[31] Timothy D Zavarella. 'A methodology for using eBPF to efficiently monitor network behavior in Linux Kubernetes clusters'. PhD thesis. Massachusetts Institute of Technology, 2022 (cit. on p. 9).

[32] Zili Zha et al. 'Towards Software Defined Measurement in Data Centers: A Comparative Study of Designs, Implementation, and Evaluation'. In: *IEEE Transactions on Cloud Computing* (2022), pp. 1–12. ISSN: 2168-7161, 2372-0018. DOI: 10.1109/TCC.2022.3181890 (cit. on p. 7).

Appendix A

Code Snippets

A.1 `sendto` Timing bpftrace Script

```
// register timestamp of 'sendto' syscall
tracepoint:syscalls:sys_enter_sendto
{
    @time[tid] = nsecs;
    @conf[tid] = tid;
}


// calculate time if 'tid' was set in 'conf' bpf map
// (ensures thread came from 'sendto')
kprobe:dev_hard_start_xmit
/@conf[tid] == tid/
{
    printf("[%d] function: %dns\n", tid, nsecs - @time[tid]);
    @conf[tid] = tid + 1;
}


// calculate time if 'tid' was reset in 'conf' map
// also delete what was stored in the bpf map
tracepoint:syscalls:sys_exit_sendto
{
    // (ensures that thread passed through 'dev_hard_start_xmit')
    if (@conf[tid] == tid + 1) {
        printf("[%d] syscall:  %dns\n", tid, nsecs - @time[tid]);
    }

    // delete stuff in the bpf map
    delete(@time[tid]);
    delete(@conf[tid]);
}
```

```
// clear anything that got stuck in the bpf map at the end
// (e.g. thread that entered 'sendto' but didn't exit yet)
END {
    clear(@time);
    clear(@conf);
}
```

Listing A.1: bpftrace script

A.2 Detect Mesh Network Function Calls

```
...

kprobe:mesh_path_send_to_gates
{
    printf("mesh_path_send_to_gates\n");
}


kprobe:mesh_path_discard_frame
{
    printf("mesh_path_discard_frame\n");
}


kprobe:mesh_path_flush_pending
{
    printf("mesh_path_flush_pending\n");
}


kprobe:mesh_path_fix_nexthop
{
    printf("mesh_path_fix_nexthop\n");
}

...
```

Listing A.2: bpftrace script