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# DEDICATION

To my loving wife and my steadfast parents,

This thesis is dedicated to you, with heartfelt gratitude and appreciation for your unwavering support, encouragement, and love throughout my academic journey. Your sacrifices, guidance, and belief in my abilities have been the pillars upon which I have built my dreams.

To my wife, you have been my rock, my inspiration, and my sanctuary. Your presence has brought joy and light into the darkest corners of this journey, and your unwavering faith in me has been a constant source of strength. Thank you for your patience, understanding, and companionship.

To my parents, your love, wisdom, and unwavering belief in the value of education have been the foundation of my aspirations. Your sacrifices and commitment to my success have not gone unnoticed, and I am forever grateful for the opportunities you have given me. I am who I am today because of your unwavering support and love.

With immense gratitude, I dedicate this thesis to you, my loving wife and my dear parents, for without you, none of this would have been possible.

# ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to everyone who has supported and guided me throughout the journey of completing this thesis.

First and foremost, I am profoundly grateful to my advisor, Dr. Prasanth for their invaluable guidance, constructive criticism, and unwavering support. Your mentorship and dedication have been instrumental in shaping my research and academic growth, and I am honored to have had the opportunity to learn from you.

# ABSTRACT

P4 programming language provides a way to configure the data plane as per the requirements. P4 programmable equipment can be configured to offload specific workloads from the application. As telecom operators embrace cloud infrastructure, the VNFs are usually hosted over COTS. One VNF can be UPF in 5G Core architecture as defined in the 3GPP standards. Our suggestion is to offload DNS packets from UPF. In this paper, we will explore the benefits and drawbacks of this approach to conclude whether it would be feasible to offload the DNS workload from UPF.

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# LIST OF ABBREVIATIONS

|  |  |
| --- | --- |
| 3GPP | 3rd Generation Partnership Project |
| 5G | 5th Generation |
| AMF | Access and Mobility Management Function |
| AVP | Attribute value pair |
| COTS | Commercial of the shelf |
| DNS | Domain name server |
| GTPU | GPRS Tunnelling Protocol |
| IP | Internet protocol |
| ISP | Internet service provider |
| NAS | Non-Access Stratus |
| NR | New Radio |
| OVSDB | Open vSwitch Database Management Protocol |
| P4 | Programming Protocol-independent Packet Processors |
| RAN | Radio Access network |
| SDN | Software defined networking |
| SMF | Session Management Function |
| TAC | Tracking Area Code |
| UE | User equipment |
| UPF | User plane function |
| URL | Uniform Resource Locator |
| VM | Virtual machine |
| VNF | virtual network function |
|  |  |

# INTRODUCTION

## Background of the Study

As the 3GPP standards have introduced a service-based architecture for 5G core, the industry is moving towards microservices over the cloud. These telecom workloads are handled mainly by COTS in a cloud environment. Since the services are running on general-purpose hardware, the performance might not be on par with the application-specific equipment. UPF can also be hosted over the cloud as VNF. As per 3GPP standards, the purpose of UPF is to handle user-plane traffic in the 5G Core mobility domain (Alain Sultan, 2022). It serves as an anchor that connects the mobility network domain with an external network. It can also serve as a policy enforcement function and enforce QoS on traffic as per the requirements (Alain Sultan, 2022). For example, if a subscriber has no quota left, the UPF would start dropping packets, including DNS packets. In this case, the UE will not be able to access the ISP’s internal services that are meant to be free, such as renewal of the subscription to avail of the ISP’s internet and calling services. For this purpose, DNS queries are made free of charge so that the UE can get the IP addresses of the intended free service by the ISP. To implement this, UPF would have to bypass the charging trigger or tag the traffic with the appropriate service-identified AVP, which is charged as free by the charging system for DNS queries, along with the free service’s URL, IP address, and port.

From the discussion above, marking DNS traffic as free by UPF can provide extra features and revenue chances for ISPs. Moreover, since all the DNS traffic would have to bypass the UPF, we can route DNS traffic toward the internet DNS instead of UPF. This approach can offload UPF from processing all these packets and result in efficient use of resources. We will explore 5G architecture and P4 language further for better understanding.

### 5G System Architecture

As per technical specification for 5G system architecture defined by (3GPP, 2023b), the 5G core network could consist of AMF, SMF, UPF, UDF, AUSF, PCF, UDM, NFF, NEF, CHF and NSSF. Please note that this is not an exhaustive list of functions, and other functions can be added with new releases as well. The overall basic 5G non-roaming architecture is shown in Figure 1-1. A picture containing diagram, text, plan, line

Description automatically generated

Figure 1‑1 5G System Architecture

Brief overview of UE registration to the 5G network is explained as below as per the (3GPP, 2023b):

1. The gNodeB delivers a Registration Request from the User Equipment (UE) to the AMF in an Initial UE Message
2. Upon receiving the Registration Request, the new AMF gathers the UE context from the previous AMF if the UE was attached previously to the network
3. The AMF authenticates the UE, using keys provided by the Authentication Server Function (AUSF), thereby setting up a secure connection at the Network Access Stratum (NAS) level
4. Next, the AMF checks the 5G Equipment Identity Register (5G-EIR) to ensure that the device is not reported as stolen
5. The AMF retrieves data related to the user's subscription from the Unified Data Management (UDM)
6. The AMF establishes a policy association with the Policy Control Function (PCF)
7. The AMF updates the Session Management Function (SMF) context
8. The SMF assigns IP address to the UE, selects a UPF and also allocated GTP Tunnel ID for UPF so that it can be shared with the gNodeB later on.
9. The SMF sends session request to the UPF so that UPF can prepare to send and receive packet for the UE
10. SMF then sends confirmation of the session creation to the AMF. This causes AMF to initiate a request to UE over NAS layer to start the default Packet Data Unit (PDU) session, along with delivering a Registration Accept message
11. After receiving confirmation from the gNodeB that the Initial Context setup is finished, the AMF updates the SMF context one more time where it informs SMF the GTP tunnel details of the gNodeB.

The UE-generated packet traverses to the UPF network via the RAN network. The UPF serves as an anchor point for the subscriber’s packet. As per the procedures mentioned by (3GPP, 2023a), one of the critical functions of the UPF is encapsulation/decapsulation of the GTP tunnel headers. The purpose of this tunnel is to maintain mobility if the UE travels from one gNodeB to another. The tunnel’s source and destination IP between the gNodeB and UPF can change, but the UE’s assigned IP address remains the same. As per the procedures defined by (3GPP, 2023b), whenever the UE moves to a new gNodeB, the AMF knows the updated IP address and GTP tunnel IDs. AMF informs the updated information to SMF, and SMF then relays this information to the UPF. Since the UPF must process all the user data, no standard is defined to bypass the UPF for particular packets. This approach allows UPF to perform specific actions before forwarding the packets to the internet. Some of these actions are listed below as defined by (3GPP, 2023a)

* Provide per subscriber usage report to the SMF
* Perform PCEF function to enforce policies received from SMF
* QoS management
* Packet inspection
* Application detection

UPF will not be able to perform these actions on the bypassed packet. So we must be cautious in selecting the type of packet that could be bypassed. Another aspect would be determining if bypassing the particular traffic would result in performance gains.

### P4 programming language

As 5G implementation are adapting the NFV and CNF technologies, Software Defined Networking has gained momentum. In SDN the flows are installed to the data-plane devices from a centralized network element often called controller or control-plane. There are different protocols available to achieve decoupling of the control-plane and data-plane such as OpenFlow which is used to install match-action rules on the data plane. To install those rule, protocols such as NETCONF, RESTCONF can be used to deliver OpenFlow messages to the controlled nodes. These OpenFlow rules can be installed on a virtual switch such as OVS which uses OVSDB to store these flow information. However, SDN has a limitation in that it assumes a fixed behavior for the network data-plane. This hampers innovation and slows down the deployment of new protocols. For example, OpenFlow can detect source IP and destination IP installed in real-time from the controller. But if we want to create a new IP packet with customized headers, then the IP address header definition on both the control and data-plane would have to be written again.

P4 language addresses this issue by introducing flexibility and providing capability to define custom header structures using it’s different data types defined by the P4\_16 specs (Consortium and others, 2018). It is an opensource programming language that is made hardware vendor agnostic for interoperability. P4 language also features match-action table which receives flow rules similar to SDN controller. However, the parsing login and actions can be customized programmatically on the P4 capable switch. P4 architecture consists of the below programmable blocks as defined under P4 specs (Consortium and others, 2018)

* Parser
* Ingress control flow
* Egress control flow

This can be demonstrated by a reference switch called VSS (Consortium and others, 2018)

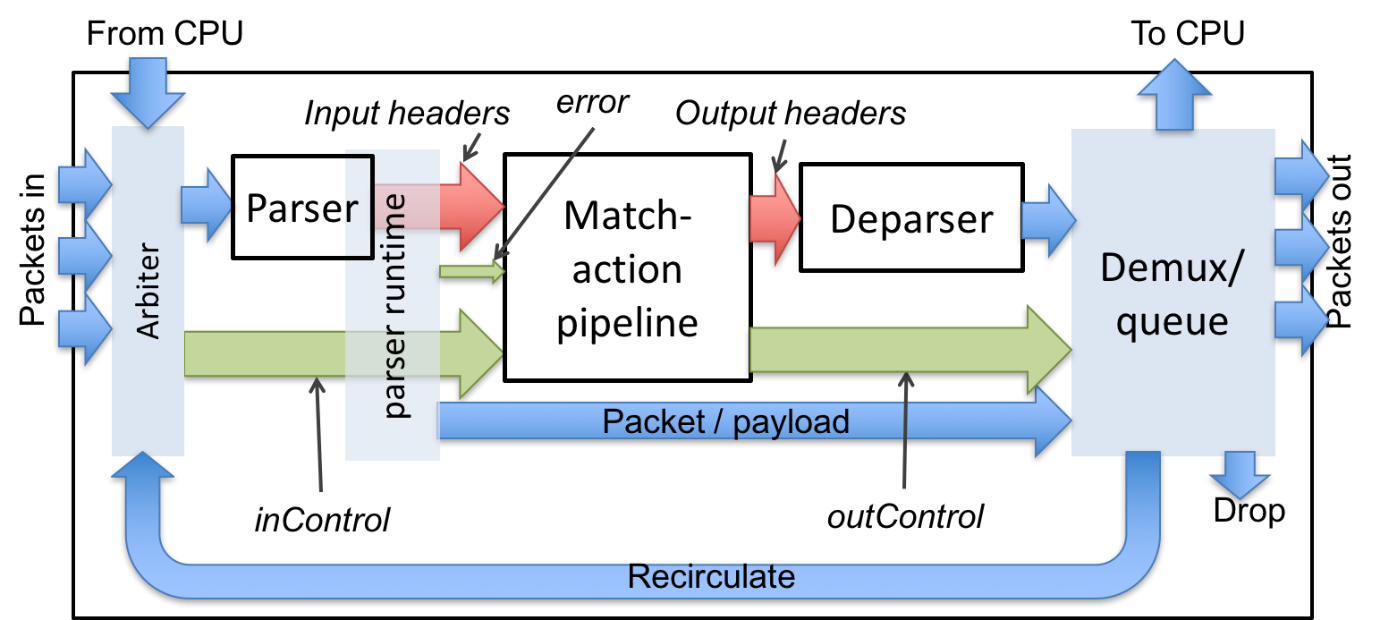


Figure 1‑2 A very simple switch (VSS) Architecture (Consortium and others, 2018)

In the figure 1-2, “inControl” is the ingress control flow and “outControl” is the egress control flow. The first programmable block that packet enters is the “Parser”. In this block we can define exactly how the packet headers will be parsed. For example, we can define complete IPv4 header as per below code.

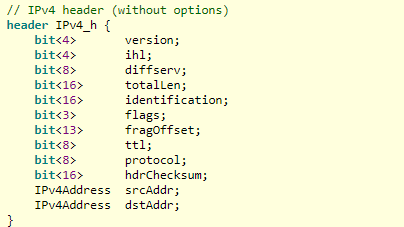


Figure 1‑3 IPv4 Header variable definition in p4 language (Consortium and others, 2018)

The packet definition above can be modified as per the requirements by simply changing the header definition. This definition can then be called under the parser block to parse the packet with the customized parsing logic.

The ingress control then provides flexibility to perform actions on the extracted headers such as changing manipulating the headers. The egress control block can have packet-out logic such as removing, adding or modifying headers. We will use P4’s flexibility to parse the UE packets inside the GTPU tunnel. We will remove the GTPU tunnel headers if these are DNS packets and forward towards DNS server for resolution, otherwise keep the headers and forward the packet to UPF.

## Problem Statement

If an ISP decides not to charge DNS packets, then the UPFs processing these packets and marking them as free would be an inefficient use of resources. A P4 based traffic offloading can result in efficient use of UPF resources. The performance gains of P4 based switches as compared to other software based packet acceleration technologies has been determined in previous studies and it was observed that P4 achieved the lowest latency for small packets (Rischke *et al.*, 2022).

In previous studies, complete UPF functionality has been implemented in a P4 programmable switch (Paolucci *et al.*, 2021). However, this might not be a feasible approach as vendors would then need to implement other UPF functionalities over the P4 switch as well. This is because key UPF features are missing such as a mechanism to trigger per UE usage reports to the SMF so that SMF can communicate with Charging Functions. Similarly, a mechanism to implement policy enforcement received by SMF from PCF is also not provided.

Considering the benefits of P4 switches P4 workload offloading from UPF has already been performed but for service function chaining which is different that routing traffic based on packet encapsulated under the GTP-U tunnel (Paolucci *et al.*, 2021). This can be a useful approach if service chaining functionality is implemented by the operator.

So, from the above discussion, P4 seems to be a good approach however implementing complete UPF functionality of the programmable data-plane or steering traffic via service chaining might not be feasible in all the scenarios. Considering the lack of implemented features or the mandatory requirement of SFC implementation that could lead to major network design changes at the service provider’s end. Our suggestion is to bypass only the DNS packets encapsulated under the GTP tunnel and assess the feasibility of this approach.

## Aim and Objectives

The main aim of this research is to conclude whether offloading DNS traffic from UPF would result in performance gain and if it would be feasible considering the drawbacks of this approach.

The research objectives are formulated based on the aim of this study which is as follows:

* To explore concerns of bypassing DNS traffic from UPF
* To suggest mitigation techniques if DNS traffic is bypassed
* To estimate the performance gains of this approach

## Research Questions

What would be the performance gain offloading DNS packets, and what are the significant concerns in bypassing the UPF for these packets?

## Scope of the Study

The scope of this study is limited to DNS traffic processing at the P4 programmable data plane switch and its impact on the 5G Network. For performance evaluation, two devices’ packet capture will be analyzed to estimate DNS traffic by a UE; the real-world traffic can vary depending on the usage, which the data collection methodology might not depict in this research work.

## Significance of the Study

Although UPF functionality can be offloaded completely to data plane switches, the drawbacks are significant because of the lack of key features (Paolucci *et al.*, 2021). We are suggesting an approach that does not require any major design changes, and the P4 code can simply be implemented over the transit switch or SmarNIC on the compute node hosting the UPF. In this approach, the key PF functionalities are retained with the COTS-based UPF instance on VM or Container. We are suggesting specifically offloading DNS packets because DNS queries are expected to be large in number as the mobile subscriber base is huge. The total number of subscribers connected to Reliance JIO ISP in March 2022 was 403.99 million (Statista and TRAI, 2022). If all the DNS packets can bypass UPF without any disadvantages, this could save a lot of UPF resources for other essential workloads.

## Structure of the Study

TBD

# LITERATURE REVIEW

## Introduction

5G network implementation has moved towards CNF and VNF-based network deployments over the COTS, making it easier for the ISP to become agile in the rollout (Attaoui *et al.*, 2023). However, hosting UPF on COTS results in packets being software accelerated. The latency performance difference between software and hardware-based packet processing has been studied recently (Rischke et al., 2022), and it was concluded that P4 based hardware packet process performs significantly better.

While existing literature suggests multiple ways to leverage P4 programmable switches and NICs in 5G networks, certain aspects still need to be considered, such as the lack of features or added complexity. This review will critically analyze these P4-based offloading and traffic steering approaches available in the existing literature. We would also assess and identify security gaps in our suggested approach to offload the DNS traffic from UPF via the P4-based NIC/Switch. This will help us identify the gaps within the implementations and the security risks involved in our suggested approach. It is important to understand the 5G core network architecture.

## UPF Offloading on P4

Efforts have been made to utilize P4 programmable data plane for offloading suitable traffic via P4 based network element. One such was performed by (Osinski et al., 2019) to offload traffic from the VNF using mico-VNFs. These micro-VNFs could be vOVS or SmarNICs. The study described performance bottlenecks in a data center architecture for Network Function Virtualization (NFV). They first conducted testing to determine if offloading packets to the DPDK based OVS running on the micro-VNF would result in better performance.

A diagram of a network

Description automatically generated with low confidence

Figure 4: VNF Traffic offload testing topology and flow (Osinski et al., 2019)

The testing was conducted

## Related Research Publications

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# APPENDIX A: RESEARCH PROPOSAL

# APPENDIX B: ETHICS FORMS