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5G network analysis for dynamic QoS and traffic management

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Abstract

Optimal Quality of Service (QoS) and efficient traffic management in 5G Non-Terrestrial Networks (NTNs) rely on the effective orchestration of communication between the various network elements. Through real-time monitoring of the 5G infrastructure, we can derive significant insights to enhance the management of these limited satellite resources. Central to this are the roles of the Session Management Function (SMF) and the User Plane Function (UPF) in governing the user plane traffic, enforcing QoS and managing sessions. The interaction between the SMF-UPF is mainly governed through the PFCP protocol.

The SMF and the UPF mainly interact using the PFCP (Packet Forwarding Control Protocol). In particular, through a *PFCP Session Establishment Request* and a *PFCP Session Establishment Response,* the SMF and the UPF are able to establish a new Protocol Data Unit (PDU) session initiated by a User Equipment (UE). The Usage Reporting Rule (URR), which is part of the *PFCP Session Establishment Request*, dictates the conditions for reporting traffic in line with policy or billing requirements. The UPF sends the *PFCP Session Report Request* to the SMF to report certain events or usage information according to the predefined usage reporting rules. This paper analyzes the SMF-UPF interaction, mainly through the PFCP protocol, with the aim of extracting crucial information that are useful for dynamic traffic and QoS management.

Keywords: 5G, free5GC, PFCP, Dynamic Traffic, QoS Management

Introduction

An intelligent orchestration of communications among diverse 5G network components can be used to enhance resource utilization in NTNs (Non-Terrestrial Networks), aiming to achieve optimal Quality of Service (QoS) and traffic management. Real time monitoring of 5G network infrastructure provides a lot of valuable information that may be used to build tools to optimize the limited available resources of satellite 5G NTNs. The Session Management Function (SMF) interacts with the User Plain Function (UPF) to manage the user plane traffic, enforce the QoS rules and handle the session management. In addition, the Usage Reporting Rule (URR) defines the conditions and parameters for reporting traffic usage as required by the network's policy or billing rules and the generated usage reports are then sent from the UPF to the SMF. The UPF sends the *PFCP Session Report Request* to the SMF to report certain events or usage information according to the predefined usage reporting rules. In this technical paper we will analyze the interaction between the SMF and the UPF, which mainly uses the PFCP (Packet Forwarding Control Protocol) protocol, with the intention of extracting useful information related to dynamic traffic and QoS management.

Interaction between the SMF and the UPF

In the following section we will make use of the deployed 5G network infrastructure developed for the TRANTOR project [1] to capture the network traffic and analyze some interesting message exchanges between the SMF and the UPF of the 5G system.

5G Packet Forwarding Control Protocol

The separation of the control and user plane functions of the core network, known as CUPS (Control and User Plane Separation), introduced in 4G LTE's later stages is also carried into 5G. PFCP is the protocol that facilitates the communication between the control plane and user plane functions, especially in the context of the interaction between the SMF and the UPF in 5G. The CUPS allows network elements to be placed closer to the end user (e.g. at the network edge). This can lead to reduced latency and better adaptability for diverse service requirements in the 5G era, such as IoT, ultra-reliable low latency communications and enhanced mobile broadband, leading to a more flexible and efficient networking allowing the possibility of introducing the concept of edge computing.

SMF handles the session management responsibilities, including establishing, maintaining and terminating the user's data sessions. UPF on the other hand deals with packet routing and forwarding. The SMF communicates with the UPF to manage the user plane traffic, enforce QoS rules and handle session management. These interactions are critical for maintaining the desired QoS and for efficient resource utilization.

Let us explore a captured message, which plays an important role in the communications between the SMF and the UPF when a User Equipment (UE) establishes a new Protocol Data Unit (PDU) session. The captured message is a *PFCP Session Establishment Request* which is part of the PFCP protocol. The message has been decoded using a python script based on the scapy library [2] and it contains various important fields as shown in *Annex 1*.

As an example, let us break down some parts of the reported *PFCP Session Establishment Request* message. The following extracted text from Annex 1 contains a QoS Flow Identifier (QFI) Information Element (IE).

```
                |   |   |###[ IE QFI ]###
                |   |   |  ietype   = QFI
                |   |   |  length   = 1
                |   |   |  spare    = 0x0
                |   |   |  QFI      = 1
                |   |   |  extra_data= ''
```

Here is a breakdown of what each part represents:

- **IEtype = QFI**. This indicates that the IE type is a QFI, meaning it's related to a QoS Flow Identifier;
- **length = 1**. This denotes the length of the IE in bytes. In this case, the length of the QFI IE is 1 byte;
- **spare = 0x0**. This represents spare bits that are reserved for future use. The value 0x0 shows that these bits are currently set to zero;
- **QFI = 1**. This is the actual QFI value in the message. The QFI is used to identify a specific QoS flow in a 5G network within the PDU session. In this case, the QFI value is 1;
- **extra_data = ''**. This indicates that there's no extra data associated with this IE.

Each QoS flow has specific QoS characteristics (e.g. guaranteed bit rate, priority level, etc.) and the QFI ensures that the correct QoS parameters are applied to the data packets as they traverse the network. The value "QFI=1" specifically refers to a QoS flow identified by the number 1. Each flow is also associated with a specific 5G QoS Identifier (5QI). Both QFI and 5QI are integral components of the QoS framework in 5G networks, but they serve different purposes:

QFI is associated with a specific QoS flow within a user's PDU session. It is used to ensure that data packets within that QoS flow receive the appropriate QoS treatment as they traverse the network. Each QoS flow can have unique QoS requirements. The QFI helps the network elements, especially the UPF, recognize and apply the appropriate treatment for each flow.

5QI is a scalar value that indicates a specific set of QoS characteristics. The 5QI defines the QoS profile for a particular type of traffic. It determines parameters like packet delay budget, packet error rate, priority level, and so on. 5QI provides a standardized way to reference specific QoS requirements in the 5G network. Standardized 5QI values have one-to-one mapping to a standardized combination of 5G QoS characteristics as specified in official 3gpp 23.501 V18.1.0 (2023-03) document [3]. The 5G QoS characteristics for pre-configured 5QI values are pre-configured in the access network (AN). Standardized or pre-configured 5G QoS characteristics are indicated through the 5QI value, and are not signaled on any interface, unless certain 5G QoS characteristics are modified. The 5G QoS characteristics for QoS Flows with dynamically assigned 5QI are signaled as part of the QoS profile. On the User Plane (N3 interface), each PDU is associated with one 5QI via the QFI carried in the encapsulation header (i.e. in the encapsulation header of the GPRS tunnel used for the PDU Session).

The following table is extracted from the 3GPP TS 23.501 V17.7.0 (2022-12) document [3] and is entitled "Standardized 5QI to QoS characteristics mapping". It shows the QoS values assigned to standardized service which may be either GBR or NGBR flows.

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget (NOTE 3)	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
1	GBR	20	100 ms (NOTE 11, NOTE 13)	10^{-2}	N/A	2000 ms	Conversational Voice
2	(NOTE 1)	40	150 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3		30	50 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages (see TS 23.287 [121]). Electricity distribution – medium voltage, Process automation monitoring
5	Non-GBR	10	100 ms NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	IMS Signalling
6	(NOTE 1)	60	300 ms (NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g. www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming

The network will ensure that these packets with, for example 5QI = 1, are treated with GBR and default priority level of 20 to maintain the quality of the voice call.

Relation between 5QI and QFI

When a new QoS flow is established for a user's session, it's associated with a specific QoS profile, which is determined by the 5QI. This QoS flow is then given a unique QFI for that session.

Thus, while the 5QI indicates what the QoS requirements are for a specific type of traffic, the QFI is used to mark individual data packets, within the GPRS Tunnel, so that they receive the treatment dictated by the associated 5QI. The following shows captured UE traffic within the UPF marked with QFI value of 1.

```
Frame 20: 144 bytes on wire (1152 bits), 144 bytes captured (1152 bits) on
interface any, id 0
Linux cooked capture v1
Internet Protocol Version 4, Src: 192.168.125.227, Dst: 192.168.125.7
User Datagram Protocol, Src Port: 2152, Dst Port: 2152
GPRS Tunneling Protocol
    Flags: 0x34
        001. .... = Version: GTP release 99 version (1)
        ...1 .... = Protocol type: GTP (1)
        .... 0... = Reserved: 0
        .... .1.. = Is Next Extension Header present?: Yes
        .... ..0. = Is Sequence Number present?: No
        .... ...0 = Is N-PDU number present?: No
    Message Type: T-PDU (0xff)
    Length: 92
    TEID: 0x0000000e (14)
    Next extension header type: PDU Session container (0x85)
    Extension header (PDU Session container)
        Extension Header Length: 1
        PDU Session Container
            0001 .... = PDU Type: UL PDU SESSION INFORMATION (1)
            .... 0000 = Spare: 0x0
            00.. .... = Spare: 0x0
            ..00 0001 = QoS Flow Identifier (QFI): 1
        Next extension header type: No more extension headers (0x00)
Internet Protocol Version 4, Src: 10.45.0.5, Dst: 8.8.8.8
Internet Control Message Protocol
```

In short, the 5QI defines the QoS characteristics, while the QFI is used to apply these characteristics to specific data flows in the network. They work together to ensure that data traffic in the 5G network gets the necessary quality treatment.

Usage Reporting Rule (URR)

Let us consider a second example related to the section titled "IE Create URR" which is part of the *PFCP Session Establishment Request* message and it contains a series of boolean flags, each representing a specific condition that might trigger the usage reporting. These triggers are defined in the 3GPP specifications for 5G networks.

```
|###[ IE Create URR ]###
|  ietype    = Create URR
|  length    = 33
|  \IE_list   \
|   |###[ IE URR ID ]###
|   |  ietype= URR ID
|   |  length= 4
|   |  id    = 1
|   |  extra_data= ''
|   |###[ IE Measurement Method ]###
|   |  ietype= Measurement Method
|   |  length= 1
|   |  spare  = 0x0
|   |  EVENT  = 0
|   |  VOLUM  = 1
|   |  DURAT  = 0
|   |  extra_data= ''
|   |###[ IE Reporting Triggers ]###
|   |  ietype= Reporting Triggers
|   |  length= 3
|   |  linked_usage_reporting= 0
|   |  dropped_dl_traffic_threshold= 0
|   |  stop_of_traffic= 0
|   |  start_of_traffic= 0
|   |  quota_holding_time= 0
|   |  time_threshold= 0
|   |  volume_threshold= 1
|   |  periodic_reporting= 0
|   |  spare  = 0x0
|   |  event_quota= 0
|   |  event_threshold= 0
|   |  mac_addresses_reporting= 0
|   |  envelope_closure= 0
|   |  time_quota= 0
|   |  volume_quota= 0
|   |  extra_data= '\x00'
|   |###[ IE Volume Threshold ]###
|   |  ietype= Volume Threshold
|   |  length= 9
|   |  spare  = 0x0
|   |  DLVOL  = 0
|   |  ULVOL  = 0
|   |  TOVOL  = 1
|   |  total  = 0x6400000
|   |  extra_data= ''
```

Here are some key parts explained:

- **IE Create URR.** This IE is initiating the creation of a URR. A URR is used in the 5G network to define the measurement and reporting rules for a specific user PDU session traffic.
- **IE URR ID.** The ID of the Usage Reporting Rule being created;
- **IE Measurement Method.** Specifies the method to measure the usage of a PDU session. The flags EVENT, VOLUM and DURAT indicate that it can be done based on events, volume or duration;
- **IE Reporting Triggers.** Defines the conditions that will trigger the reporting of usage information;
- **IE Volume Threshold.** Specifies the volume threshold for usage reporting. This indicates when usage reporting should be triggered based on the volume of traffic.

In this context, a value of 0 typically indicates that the corresponding reporting trigger is disabled, meaning that the specific condition will not trigger usage reporting. On the other hand, a value of 1 indicates that the corresponding reporting trigger is enabled, so when that condition is met, it will trigger usage reporting.

Looking at the individual flags:

- **linked_usage_reporting.** Indicates if the usage reporting is linked to another reporting;
- **dropped_dl_traffic_threshold.** Trigger when the volume of dropped downlink traffic exceeds a certain threshold;
- **stop_of_traffic.** Trigger when the traffic stops.
- **start_of_traffic.** Trigger when the traffic starts.
- **quota_holding_time.** Trigger when the time a quota has been held exceeds a certain threshold.
- **time_threshold.** Trigger when the duration of traffic exceeds a certain threshold;
- **volume_threshold.** Trigger when the volume of traffic exceeds a certain threshold;
- **periodic_reporting.** Indicates if reporting should be done periodically.
- **event_quota.** Trigger when the number of events exceeds a certain quota.
- **event_threshold.** Trigger when the number of events exceeds a certain threshold.
- **mac_addresses_reporting.** Indicates if reporting should include MAC addresses.
- **envelope_closure.** Trigger when an envelope (a defined quantity of user plane traffic) is closed.
- **time_quota**: Trigger when the time of traffic exceeds a certain quota.
- **volume_quota**: Trigger when the volume of traffic exceeds a certain quota.

In the given example, only the **volume_threshold** flag is set to 1, which means that usage reporting will be triggered when the volume of traffic exceeds a certain threshold. The rest of the conditions are set to 0, meaning they won't trigger usage reporting.

The values of these reporting triggers are usually configured by network administrators, often as part of the SMF in a 5G network. The SMF is responsible for handling session management in the control plane of a 5G network, including the establishment, modification, and release of PDU sessions. As part of this, the SMF sends messages to the UPF to establish or modify the rules for user plane traffic measurement and reporting.

When a PDU session is established or modified, the SMF can include a Create URR IE in the message to the UPF. This IE includes a Reporting Triggers IE, which specifies the conditions that should trigger usage reporting for this PDU session.

The values of the individual reporting triggers are set by the network administrators based on the specific needs and policies of the network. This can be done manually or by using automated network management tools and the exact method can depend on the specific network equipment and software being used.

The configuration of these reporting triggers can be updated as needed, for example to adjust to changes in the network traffic patterns, network policies or quality of service requirements. When a change is needed, the SMF sends a new message to the UPF to modify the existing URR or create a new one with the updated reporting triggers.

QoS Enforcement Rule (QER)
The QoS Enforcement Rule (QER) is a concept in 5G networks, and it plays a vital role in managing and enforcing QoS for user data flows within the network. Specifically, the QER is used to determine how packets are treated as they traverse the 5G core network, especially at the UPF.

Here is a third and a last example:

```
|###[ IE Create QER ]###
|  ietype    = Create QER
|  length    = 32
|  \IE_list   \
|   |###[ IE QER ID ]###
|   |  ietype= QER ID
|   |  length= 4
|   |  id    = 1
|   |  extra_data= ''
|   |###[ IE Gate Status ]###
|   |  ietype= Gate Status
|   |  length= 1
|   |  spare = 0x0
|   |  ul    = OPEN
|   |  dl    = OPEN
|   |  extra_data= ''
|   |###[ IE MBR ]###
|   |  ietype= MBR
|   |  length= 10
|   |  ul    = 1073741
|   |  dl    = 1073741
|   |  extra_data= ''
|   |###[ IE QFI ]###
|   |  ietype= QFI
|   |  length= 1
|   |  spare = 0x0
|   |  QFI   = 1
|   |  extra_data= ''
```

The provided text is part of *PFCP Session Establishment Request* which has been captured and decoded using a python script based on the scapy library. Here are some key parts explained:

- **IE Create QER**. This IE initiates the creation of a QER
- **IE QER ID**. The ID of the QER being created.
- **IE Gate Status.** Specifies the status of gates for uplink (UL) and downlink (DL) traffic. Gates can be used to control (open or close) the flow of traffic.
- **IE MBR** (Maximum Bit Rate). This indicates the maximum allowed bit rate for uplink and downlink traffic.
- **IE QFI**. Specifies the QFI associated with the QER being created.

The QER is in charge of the following functions:

- **Packet Filtering.** QER contains rules that help in identifying specific packets. This identification is based on various parameters like source and destination IP, port numbers, etc.
- **QoS Handling.** Once the packets are identified, the QER dictates the QoS treatment to be applied. This includes:
  - **QFI assignment**. As mentioned earlier, QFI determines the QoS flow for a specific packet, which in turn dictates its treatment in the network.
  - **Forwarding Action** (e.g. whether to drop the packet, forward it or mark it for certain treatment).
  - **Buffering and marking of packets**.
- **Traffic Steering**. QER can also dictate how the traffic should be steered, for instance:
  - Redirecting specific flows to certain services (e.g. a content delivery network or a parental control service).
  - Load balancing decisions.
  - Directing traffic to specific transport network layers.
- **Rate Control.** QER can include rules about the allowed data rates for certain flows, thereby enabling:
  - Guaranteeing a minimum bit rate for specific services.
  - Applying a maximum bit rate to prevent network resource abuse.
- **Usage Reporting.** It is also responsible for tracking and reporting the amount of data for each QoS flow. This can be useful for billing purposes, QoS assurance and network analytics.

Session Report Request message

Another important message which is part of PFCP is *Session Report Request* which is used in 5G networks, particularly between the SMF and the UPF. The primary purpose and scenarios for using this message are:

- **Usage Reporting**. The main use of the *PFCP Session Report Request* message is for the UPF to inform the SMF about certain events or metrics that have occurred within a particular session as requested during the *PFCP Session Establishment Request*. This is typically related to the amount of data that's been transmitted or received (usage reporting). This information helps the SMF understand how a specific session is being used, which is essential for billing, quota management and policy control.
- **Event Reporting**. Beyond just data usage, the UPF might also report other events to the SMF, such as if a predefined volume threshold has been reached, if the session has been active for a certain duration or other conditions set by the SMF or defined by policy.
- **Enabling Reactive Management**. Upon receiving such a report, the SMF can make decisions based on the reported information. For instance, if a data usage threshold is reached, the SMF might decide to adjust the QoS for the session, redirect the traffic, or even terminate the session.
- **Support for Policy Control**. The reported metrics and events can also be fed back into the PCF to allow dynamic policy decisions based on real-time usage data.

- **Billing and Charging.** Usage reports are critical for charging and billing systems. They ensure that users are billed correctly based on their actual data usage.
- **Monitoring and Analytics.** These reports can be fed into analytics systems to monitor network health, user behavior, and other metrics.

In summary, the *PFCP Session Report Request* message is an essential component in the 5G core network that facilitates a feedback loop from the UPF back to the SMF, allowing for dynamic session management based on real-time usage and events.

Each *PFCP Session Report Request*, which is related to a specific UE PDU session, is uniquely identified by a Session Endpoint Identifier (SEID). SEID is a globally unique identifier used for CP function to UP function communication and is utilized in various messages for uniquely identifying PDU sessions. In the following example, a SEID value of 0x0000000000000001 is utilized to uniquely identify PDU sessions:

```
Packet Forwarding Control Protocol
    Flags: 0x21, SEID (S)
    Message Type: PFCP Session Report Request (56)
    Length: 209
    SEID: 0x0000000000000001
    Sequence Number: 13
    Spare: 0
```

As an example, let us now analyze a captured *PFCP Session Report Request* using our free5GC-based 5G research infrastructure [4], [5].

```
###[ PFCP Session Report Request ]###
             \IE_list   \
             |###[ IE Report Type ]###
             |  ietype     = Report Type
             |  length     = 1
             |  spare      = 0x0
             |  UPIR       = 0
             |  ERIR       = 0
             |  USAR       = 1
             |  DLDR       = 0
             |  extra_data= ''
             |###[ IE Usage Report (Session Report Request) ]###
             |  ietype     = Usage Report (Session Report Request)
             |  length     = 116
             |  \IE_list    \
             |   |###[ IE URR ID ]###
             |   |  ietype= URR ID
             |   |  length= 4
             |   |  id     = 1
             |   |  extra_data= ''
             |   |###[ IE UR-SEQN ]###
             |   |  ietype= UR-SEQN
             |   |  length= 4
             |   |  number= 1
             |   |###[ IE Usage Report Trigger ]###
             |   |  ietype= Usage Report Trigger
             |   |  length= 3
             |   |  IMMER  = 0
             |   |  DROTH  = 0
```

```
            |   |  STOPT  = 0
            |   |  START  = 0
            |   |  QUHTI  = 0
            |   |  TIMTH  = 0
            |   |  VOLTH  = 1
            |   |  PERIO  = 0
            |   |  EVETH  = 0
            |   |  MACAR  = 0
            |   |  ENVCL  = 0
            |   |  MONIT  = 0
            |   |  TERMR  = 0
            |   |  LIUSA  = 0
            |   |  TIMQU  = 0
            |   |  VOLQU  = 0
            |   |  extra_data= '\x00'
            |   |###[ IE Start Time ]###
            |   |  ietype= Start Time
            |   |  length= 4
            |   |  timestamp = 3894541741
            |   |  extra_data= ''
            |   |###[ IE End Time ]###
            |   |  ietype= End Time
            |   |  length= 4
            |   |  timestamp = 3894542047
            |   |  extra_data= ''
            |   |###[ IE Volume Measurement ]###
            |   |  ietype= Volume Measurement
            |   |  length= 49
            |   |  spare  = 0x7
            |   |  DLVOL  = 1
            |   |  ULVOL  = 1
            |   |  TOVOL  = 1
            |   |  total  = 0x64002d3
            |   |  uplink= 0x0
            |   |  downlink  = 0x64002d3
            |   |  extra_data=
'\x00\x00\x00\x00\x00\x01$\\x9d\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x0
0\x01$\\x9d'
            |   |###[ IE Duration Measurement ]###
            |   |  ietype= Duration Measurement
            |   |  length= 4
            |   |  duration  = 306
            |   |  extra_data= ''
            |   |###[ IE Time of First Packet ]###
            |   |  ietype= Time of First Packet
            |   |  length= 4
            |   |  timestamp = 3894541709
            |   |  extra_data= ''
            |   |###[ IE Time of Last Packet ]###
            |   |  ietype= Time of Last Packet
            |   |  length= 4
            |   |  timestamp = 3894542047
            |   |  extra_data= ''
```

A synthetic break down of the captured *PFCP Session Report Request* describing the functionalities are reported as follows:

- **IE Report Type.** This IE defines the report type.
    - **USAR** (Usage Report) is set to 1, which means the report contains usage information.

- **IE Usage Report**. This IE is the main body containing the usage report details.
  - **IE URR ID**. This IE has an ID of 1 which is an identifier for the URR.
  - **IE UR-SEQN**. The sequence number of the usage report is 1.
  - **IE Usage Report Trigger**.
    - **VOLTH** (Volume Threshold) is set to 1, indicating the report was triggered because a volume threshold was reached.
  - **IE Start Time** and **IE End Time**. These IEs provide the start and end times of the reporting period. They are represented as seconds from the 1st January 1900:
    - the **Start Time** of *3894541741 seconds* corresponds to *May 31, 2023 17:09:01 UTC*;
    - the **End Time** of *3894542047 seconds* corresponds to *May 31, 2023 17:14:07 UTC*.
  - **IE Volume Measurement**. This IE provides data volume details.
    - **DLVOL**, **ULVOL** and **TOVOL** flags are set, indicating that the report includes Downlink Volume, Uplink Volume and Total Volume respectively.
      - The reported downlink volume is *0x64002d3*.
  - **IE Duration Measurement**. This IE reports the duration of the flow, and it lasted for 306 time units in seconds.
  - **IE Time of First Packet** and **IE Time of Last Packet**. These IEs give timestamps for the first and last packets in the reporting period (*3894541709* and *3894542047* respectively).

In essence, this *PFCP Session Report Request* message contains details about a specific session, primarily its usage. The report was triggered due to a volume threshold being reached and provides information on the volume of data transferred during the session (particularly in the downlink direction), the duration of the flow and timestamps related to the first and the last packet.

Conclusion

5G NTNs present unique challenges, particularly in terms of traffic management and maintaining QoS due to a limited amount of networking resources and environmental factors such as satellite orbital dynamics, atmospheric interference and extended signal latency. The deployment of a free5GC testbed serves as an experimental platform of crucial importance to investigate this scenario within the TRANTOR project. Free5GC, an open-source 5G core network project, offers a practical, cost-effective and accessible platform for experimentation, monitoring and analysis of 5G networks. When focused on NTNs, which include satellite and airborne platforms, the testbed becomes an indispensable instrument to develop flexible 6G non-terrestrial access architectures capable of dynamic traffic and QoS management. The distinct nature of NTN traffic, influenced by factors such as extended latency, orbital dynamics and interference, necessitates specialized monitoring and analysis tools.

By deploying a free5GC testbed, we can closely simulate, monitor and assess the behavior of data flows within a 5G NTN environment. It allows for a real-time understanding of how traffic is managed, how QoS is maintained and where potential bottlenecks or inefficiencies may arise. This invaluable data-driven insight can guide optimization strategies, ensuring that NTNs deliver consistent and reliable performance, even in challenging conditions.

Annex 1

A complete capture of a packet containing a *PFCP Session Establishment Request*.

```
###[ Ethernet ]###
  dst          = 00:50:56:b6:75:e2
  src          = 00:50:56:b6:94:a8
  type         = IPv4
###[ IP ]###
       version   = 4
       ihl     = 5
       tos     = 0x0
       len     = 653
       id      = 26233
       flags   = DF
       frag    = 0
       ttl     = 64
       proto   = udp
       chksum  = 0x568a
       src     = 192.168.125.4
       dst     = 192.168.125.7
       \options   \
###[ UDP ]###
       sport   = 8805
       dport   = 8805
       len     = 633
       chksum  = 0x7de7
###[ PFCP (v1) Header ]###
       version   = 1
       spare_b2  = 0x0
       spare_b3  = 0x0
       spare_b4  = 0x0
       MP      = 0
       S       = 1
       message_type= session_establishment_request
       length  = 621
       seid    = 0x0
       seq     = 697556
       spare_oct = 0
###[ PFCP Session Establishment Request ]###
              \IE_list   \
              |###[ IE Node ID ]###
              |  ietype      = Node ID
              |  length      = 17
              |  spare       = 0x0
              |  id_type   = IPv6
              |  ipv6        = ::1
              |  extra_data= ''
              |###[ IE F-SEID ]###
              |  ietype      = F-SEID
              |  length      = 29
              |  spare       = 0x0
              |  v4          = 1
              |  v6          = 1
              |  seid        = 0x9
              |  ipv4        = 192.168.125.4
              |  ipv6        = ::1
              |  extra_data= ''
              |###[ IE Create PDR ]###
              |  ietype      = Create PDR
              |  length      = 69
              |  \IE_list   \
              |   |###[ IE PDR ID ]###
              |   |  ietype  = PDR ID
              |   |  length  = 2
              |   |  id      = 1
              |   |  extra_data= ''
              |   |###[ IE Precedence ]###
```

```
                |   |  ietype  = Precedence
                |   |  length  = 4
                |   |  precedence= 255
                |   |  extra_data= ''
                |   |###[ IE PDI ]###
                |   |  ietype  = PDI
                |   |  length  = 27
                |   |  \IE_list   \
                |   |   |###[ IE Source Interface ]###
                |   |   |  ietype     = Source Interface
                |   |   |  length     = 1
                |   |   |  spare      = 0x0
                |   |   |  interface = Core
                |   |   |  extra_data= ''
                |   |   |###[ IE Network Instance ]###
                |   |   |  ietype     = Network Instance
                |   |   |  length     = 9
                |   |   |  instance  = 'internet'
                |   |   |###[ IE UE IP Address ]###
                |   |   |  ietype     = UE IP Address
                |   |   |  length     = 5
                |   |   |  spare      = 0x0
                |   |   |  SD         = 1
                |   |   |  V4         = 1
                |   |   |  V6         = 0
                |   |   |  ipv4       = 10.45.0.10
                |   |   |  extra_data= ''
                |   |###[ IE FAR ID ]###
                |   |  ietype  = FAR ID
                |   |  length  = 4
                |   |  id      = 1
                |   |  extra_data= ''
                |   |###[ IE URR ID ]###
                |   |  ietype  = URR ID
                |   |  length  = 4
                |   |  id      = 1
                |   |  extra_data= ''
                |   |###[ IE QER ID ]###
                |   |  ietype  = QER ID
                |   |  length  = 4
                |   |  id      = 1
                |   |  extra_data= ''
                |###[ IE Create PDR ]###
                |  ietype      = Create PDR
                |  length      = 78
                |  \IE_list   \
                |   |###[ IE PDR ID ]###
                |   |  ietype  = PDR ID
                |   |  length  = 2
                |   |  id      = 2
                |   |  extra_data= ''
                |   |###[ IE Precedence ]###
                |   |  ietype  = Precedence
                |   |  length  = 4
                |   |  precedence= 255
                |   |  extra_data= ''
                |   |###[ IE PDI ]###
                |   |  ietype  = PDI
                |   |  length  = 38
                |   |  \IE_list   \
                |   |   |###[ IE Source Interface ]###
                |   |   |  ietype     = Source Interface
                |   |   |  length     = 1
                |   |   |  spare      = 0x0
                |   |   |  interface = Access
                |   |   |  extra_data= ''
                |   |   |###[ IE F-TEID ]###
                |   |   |  ietype     = F-TEID
```

```
|   |   |  length     = 2
|   |   |  spare      = 0x0
|   |   |  CHID       = 1
|   |   |  CH         = 1
|   |   |  V6         = 1
|   |   |  V4         = 1
|   |   |  choose_id = 5
|   |   |  extra_data= ''
|   |   |###[ IE Network Instance ]###
|   |   |  ietype     = Network Instance
|   |   |  length     = 9
|   |   |  instance  = 'internet'
|   |   |###[ IE UE IP Address ]###
|   |   |  ietype     = UE IP Address
|   |   |  length     = 5
|   |   |  spare      = 0x0
|   |   |  SD         = 0
|   |   |  V4         = 1
|   |   |  V6         = 0
|   |   |  ipv4       = 10.45.0.10
|   |   |  extra_data= ''
|   |   |###[ IE QFI ]###
|   |   |  ietype     = QFI
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  QFI        = 1
|   |   |  extra_data= ''
|   |###[ IE Outer Header Removal ]###
|   |  ietype  = Outer Header Removal
|   |  length  = 2
|   |  header  = GTP-U/UDP/IPv4
|   |  spare   = 0x0
|   |  pdu_session_container= 1
|   |  extra_data= ''
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 2
|   |  extra_data= ''
|   |###[ IE QER ID ]###
|   |  ietype  = QER ID
|   |  length  = 4
|   |  id      = 1
|   |  extra_data= ''
|###[ IE Create PDR ]###
|  ietype      = Create PDR
|  length      = 62
|  \IE_list   \
|   |###[ IE PDR ID ]###
|   |  ietype  = PDR ID
|   |  length  = 2
|   |  id      = 3
|   |  extra_data= ''
|   |###[ IE Precedence ]###
|   |  ietype  = Precedence
|   |  length  = 4
|   |  precedence= 1000
|   |  extra_data= ''
|   |###[ IE PDI ]###
|   |  ietype  = PDI
|   |  length  = 23
|   |  \IE_list   \
|   |   |###[ IE Source Interface ]###
|   |   |  ietype     = Source Interface
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  interface = CP-function
|   |   |  extra_data= ''
```

```
|   |   |###[ IE F-TEID ]###
|   |   |  ietype     = F-TEID
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  CHID       = 0
|   |   |  CH         = 1
|   |   |  V6         = 1
|   |   |  V4         = 1
|   |   |  extra_data= ''
|   |   |###[ IE Network Instance ]###
|   |   |  ietype     = Network Instance
|   |   |  length     = 9
|   |   |  instance  = 'internet'
|   |###[ IE Outer Header Removal ]###
|   |  ietype  = Outer Header Removal
|   |  length  = 1
|   |  header  = GTP-U/UDP/IPv4
|   |  extra_data= ''
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 1
|   |  extra_data= ''
|   |###[ IE QER ID ]###
|   |  ietype  = QER ID
|   |  length  = 4
|   |  id      = 1
|   |  extra_data= ''
|###[ IE Create PDR ]###
|  ietype      = Create PDR
|  length      = 110
|  \IE_list   \
|   |###[ IE PDR ID ]###
|   |  ietype  = PDR ID
|   |  length  = 2
|   |  id      = 4
|   |  extra_data= ''
|   |###[ IE Precedence ]###
|   |  ietype  = Precedence
|   |  length  = 4
|   |  precedence= 1
|   |  extra_data= ''
|   |###[ IE PDI ]###
|   |  ietype  = PDI
|   |  length  = 79
|   |  \IE_list   \
|   |   |###[ IE Source Interface ]###
|   |   |  ietype     = Source Interface
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  interface = Access
|   |   |  extra_data= ''
|   |   |###[ IE F-TEID ]###
|   |   |  ietype     = F-TEID
|   |   |  length     = 2
|   |   |  spare      = 0x0
|   |   |  CHID       = 1
|   |   |  CH         = 1
|   |   |  V6         = 1
|   |   |  V4         = 1
|   |   |  choose_id = 5
|   |   |  extra_data= ''
|   |   |###[ IE Network Instance ]###
|   |   |  ietype     = Network Instance
|   |   |  length     = 9
|   |   |  instance  = 'internet'
|   |   |###[ IE SDF Filter ]###
|   |   |  ietype     = SDF Filter
```

```
|   |   |  length     = 46
|   |   |  spare      = 0x0
|   |   |  BID        = 0
|   |   |  FL         = 0
|   |   |  SPI        = 0
|   |   |  TTC        = 0
|   |   |  FD         = 1
|   |   |  spare_oct = 0
|   |   |  flow_description_length= 42
|   |   |  flow_description= 'permit out 58 from ff02::2/128 to assigned'
|   |   |  extra_data= ''
|   |   |###[ IE QFI ]###
|   |   |  ietype     = QFI
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  QFI        = 1
|   |   |  extra_data= ''
|   |###[ IE Outer Header Removal ]###
|   |  ietype  = Outer Header Removal
|   |  length  = 1
|   |  header  = GTP-U/UDP/IPv4
|   |  extra_data= ''
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 3
|   |  extra_data= ''
|###[ IE Create FAR ]###
|  ietype      = Create FAR
|  length      = 19
|  \IE_list   \
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 1
|   |  extra_data= ''
|   |###[ IE Apply Action ]###
|   |  ietype  = Apply Action
|   |  length  = 2
|   |  spare   = 0x0
|   |  DUPL    = 0
|   |  NOCP    = 1
|   |  BUFF    = 1
|   |  FORW    = 0
|   |  DROP    = 0
|   |  extra_data= '\x00'
|   |###[ IE BAR ID ]###
|   |  ietype  = BAR ID
|   |  length  = 1
|   |  id      = 1
|   |  extra_data= ''
|###[ IE Create FAR ]###
|  ietype      = Create FAR
|  length      = 36
|  \IE_list   \
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 2
|   |  extra_data= ''
|   |###[ IE Apply Action ]###
|   |  ietype  = Apply Action
|   |  length  = 2
|   |  spare   = 0x0
|   |  DUPL    = 0
|   |  NOCP    = 0
|   |  BUFF    = 0
|   |  FORW    = 1
```

```
|   |  DROP    = 0
|   |  extra_data= '\x00'
|   |###[ IE Forwarding Parameters ]###
|   |  ietype  = Forwarding Parameters
|   |  length  = 18
|   |  \IE_list   \
|   |   |###[ IE Destination Interface ]###
|   |   |  ietype     = Destination Interface
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  interface = Core
|   |   |  extra_data= ''
|   |   |###[ IE Network Instance ]###
|   |   |  ietype     = Network Instance
|   |   |  length     = 9
|   |   |  instance  = 'internet'
|###[ IE Create FAR ]###
|  ietype      = Create FAR
|  length      = 66
|  \IE_list   \
|   |###[ IE FAR ID ]###
|   |  ietype  = FAR ID
|   |  length  = 4
|   |  id      = 3
|   |  extra_data= ''
|   |###[ IE Apply Action ]###
|   |  ietype  = Apply Action
|   |  length  = 2
|   |  spare   = 0x0
|   |  DUPL    = 0
|   |  NOCP    = 0
|   |  BUFF    = 0
|   |  FORW    = 1
|   |  DROP    = 0
|   |  extra_data= '\x00'
|   |###[ IE Forwarding Parameters ]###
|   |  ietype  = Forwarding Parameters
|   |  length  = 48
|   |  \IE_list   \
|   |   |###[ IE Destination Interface ]###
|   |   |  ietype     = Destination Interface
|   |   |  length     = 1
|   |   |  spare      = 0x0
|   |   |  interface = CP-function
|   |   |  extra_data= ''
|   |   |###[ IE Network Instance ]###
|   |   |  ietype     = Network Instance
|   |   |  length     = 9
|   |   |  instance  = 'internet'
|   |   |###[ IE Outer Header Creation ]###
|   |   |  ietype     = Outer Header Creation
|   |   |  length     = 26
|   |   |  STAG       = 0
|   |   |  CTAG       = 0
|   |   |  IPV6       = 0
|   |   |  IPV4       = 0
|   |   |  UDPIPV6   = 0
|   |   |  UDPIPV4   = 0
|   |   |  GTPUUDPIPV6= 1
|   |   |  GTPUUDPIPV4= 1
|   |   |  spare      = 0
|   |   |  TEID       = 0x9
|   |   |  ipv4       = 192.168.125.4
|   |   |  ipv6       = ::1
|   |   |  extra_data= ''
|###[ IE Create URR ]###
|  ietype      = Create URR
|  length      = 33
```

```
               |  \IE_list   \
               |   |###[ IE URR ID ]###
               |   |  ietype  = URR ID
               |   |  length  = 4
               |   |  id      = 1
               |   |  extra_data= ''
               |   |###[ IE Measurement Method ]###
               |   |  ietype  = Measurement Method
               |   |  length  = 1
               |   |  spare   = 0x0
               |   |  EVENT   = 0
               |   |  VOLUM   = 1
               |   |  DURAT   = 0
               |   |  extra_data= ''
               |   |###[ IE Reporting Triggers ]###
               |   |  ietype  = Reporting Triggers
               |   |  length  = 3
               |   |  linked_usage_reporting= 0
               |   |  dropped_dl_traffic_threshold= 0
               |   |  stop_of_traffic= 0
               |   |  start_of_traffic= 0
               |   |  quota_holding_time= 0
               |   |  time_threshold= 0
               |   |  volume_threshold= 1
               |   |  periodic_reporting= 0
               |   |  spare   = 0x0
               |   |  event_quota= 0
               |   |  event_threshold= 0
               |   |  mac_addresses_reporting= 0
               |   |  envelope_closure= 0
               |   |  time_quota= 0
               |   |  volume_quota= 0
               |   |  extra_data= '\x00'
               |   |###[ IE Volume Threshold ]###
               |   |  ietype  = Volume Threshold
               |   |  length  = 9
               |   |  spare   = 0x0
               |   |  DLVOL   = 0
               |   |  ULVOL   = 0
               |   |  TOVOL   = 1
               |   |  total   = 0x6400000
               |   |  extra_data= ''
               |###[ IE Create QER ]###
               |  ietype      = Create QER
               |  length      = 32
               |  \IE_list   \
               |   |###[ IE QER ID ]###
               |   |  ietype  = QER ID
               |   |  length  = 4
               |   |  id      = 1
               |   |  extra_data= ''
               |   |###[ IE Gate Status ]###
               |   |  ietype  = Gate Status
               |   |  length  = 1
               |   |  spare   = 0x0
               |   |  ul      = OPEN
               |   |  dl      = OPEN
               |   |  extra_data= ''
               |   |###[ IE MBR ]###
               |   |  ietype  = MBR
               |   |  length  = 10
               |   |  ul      = 1073741
               |   |  dl      = 1073741
               |   |  extra_data= ''
               |   |###[ IE QFI ]###
               |   |  ietype  = QFI
               |   |  length  = 1
               |   |  spare   = 0x0
```

```
               |   |  QFI      = 1
               |   |  extra_data= ''
               |###[ IE Create BAR ]###
               |  ietype      = Create BAR
               |  length      = 5
               |  \IE_list   \
               |   |###[ IE BAR ID ]###
               |   |  ietype  = BAR ID
               |   |  length  = 1
               |   |  id      = 1
               |   |  extra_data= ''
               |###[ IE PDN Type ]###
               |  ietype      = PDN Type
               |  length      = 1
               |  spare       = 0x0
               |  pdn_type  = IPv6
               |  extra_data= ''
```

References

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[4] Home page of the free5GC project - https://free5gc.org/

[5] A. De Vita; A. Gebrehiwot; F. M. Lauria - A software-based 5G infrastructure for the TRANTOR project - Technical Report - https://publications.cnr.it/doc/486993