# Mobile Cellular Communications (5G)

## I. Objectives

The objectives of this laboratory are:

- Identify configuration parameters required for the different components
- Understand the main procedures in a mobile cellular (5G) at the control and data planes by running opensource implementations of the main components

## II. Duration

This laboratory should last 2h30.

## III. Used tools

This laboratory will use:

a) An opensource implementation of a 5G Core: Free5GC [free5Gcore]
b) A gNB and UE opensource implementation: UERANSIM [ueransim]
c) A VirtualBox VM with both components already installed in the laboratory PCs
d) Wireshark also installed in the laboratory PCs

The VM is also available via SSH at port 2222 for user '***ubuntu***' (e.g. '***ssh -p 222 ubuntu@localhost***', from the hosting machine); password is '***ubuntu***' for users '***ubuntu***' and root.

## IV. Network diagram

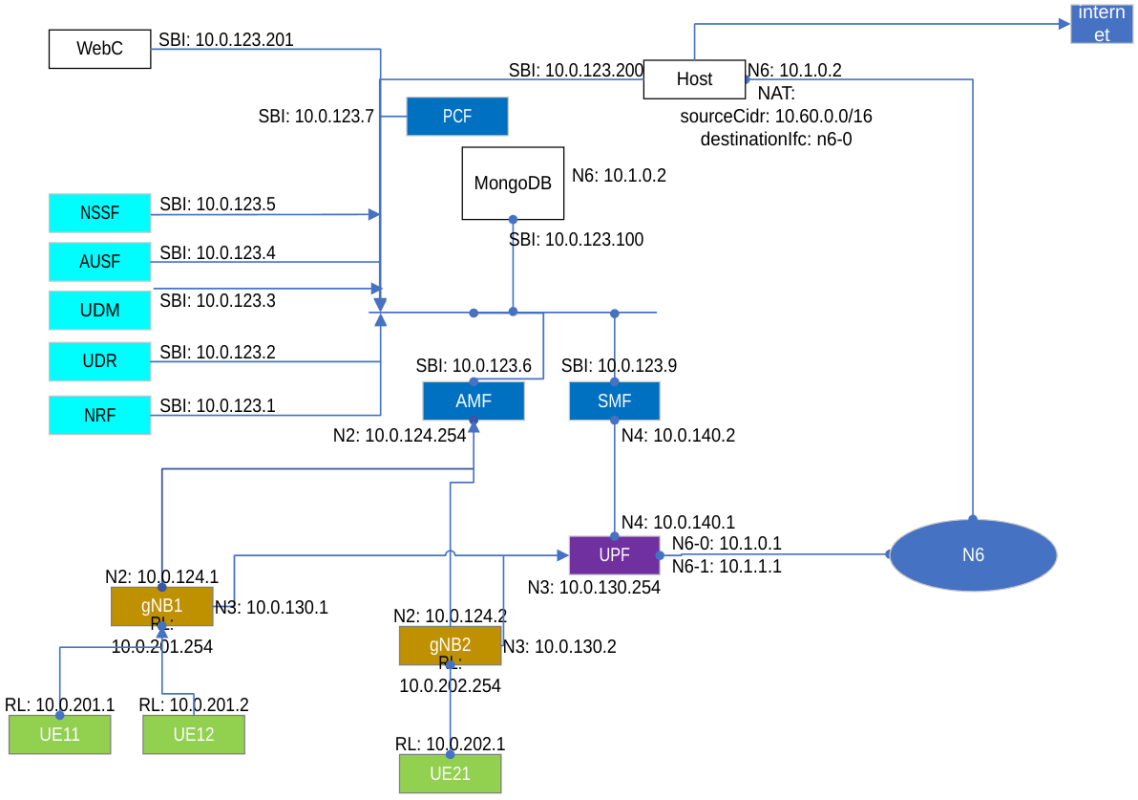



***Figure 1: Network diagram***

**Notes:**

1. 5G Core components are represented by dark and light blue boxes, gNBs by brown boxes and UEs by green boxes
2. With UERANSIM, the 5G-NR radio interface ('Radio Link') is emulated over UDP between the UEs (11, 12 and 21, green boxes) and the gNBs (gNB1 and gNB2) they are connected to.
3. IP addresses:
   a. 10.0.123.0/24: SBI; Core components, Web Console and DB (control plane)
   b. 10.0.124.0/24: N2 interfaces (control plane)
   c. 10.0.130.0/24: N3 interfaces (data plane)
   d. 10.0.140.0/24: N4 interfaces (control plane)
   e. 10.0.20[1|2].0/24: radio interfaces emulation
   f. 10.1.[1|2].0/24: N6 DNNs (data plane)
4. Via the 'Host', emulated UEs can reach the Internet A ***hosts*** file has been added to Wireshark (***/root/.config/wireshark***) for IP addresses resolution so that Wireshark presents components' names instead of IP addresses and you can better interpret the messages exchange (see that file contents in Annex F at the end).
5. The shown MongoDB in the diagram component serves as persistent data repository for the other components while the network is running.

## V. Procedure

During the laboratory execution (VirtualBox Virtual Machine), the 5G network components will be started and stop following this order:

1. **5G Network:** **5G Core (2) –> gNB1 (3.3) –> gNB2 (3.5) –>**
2. **UEs creation:** **–> UE provisioning at the 5G Core (4.2) –>**
3. **UEs start:** **–> UE11 (4.4) –> UE12 (5.5) –> UE21 (5.7) –>**
4. **Stop the system: –> UEs, gNBs and 5G Core (8.1 and 8.3)**

Linux Namespaces are used to have each of the nine 5GC Network Functions (AMF, AUSF, NRF, NSSF, PCF, SMF, UDM, UDR, UPF) running inside its own namespace [konrad]. This allows the usage of Wireshark (shall be started with 'sudo') to capture traffic packets exchanged between any two NF, on their own interfaces (you will next figure when selecting capturing interfaces after 5G Core components have been started).

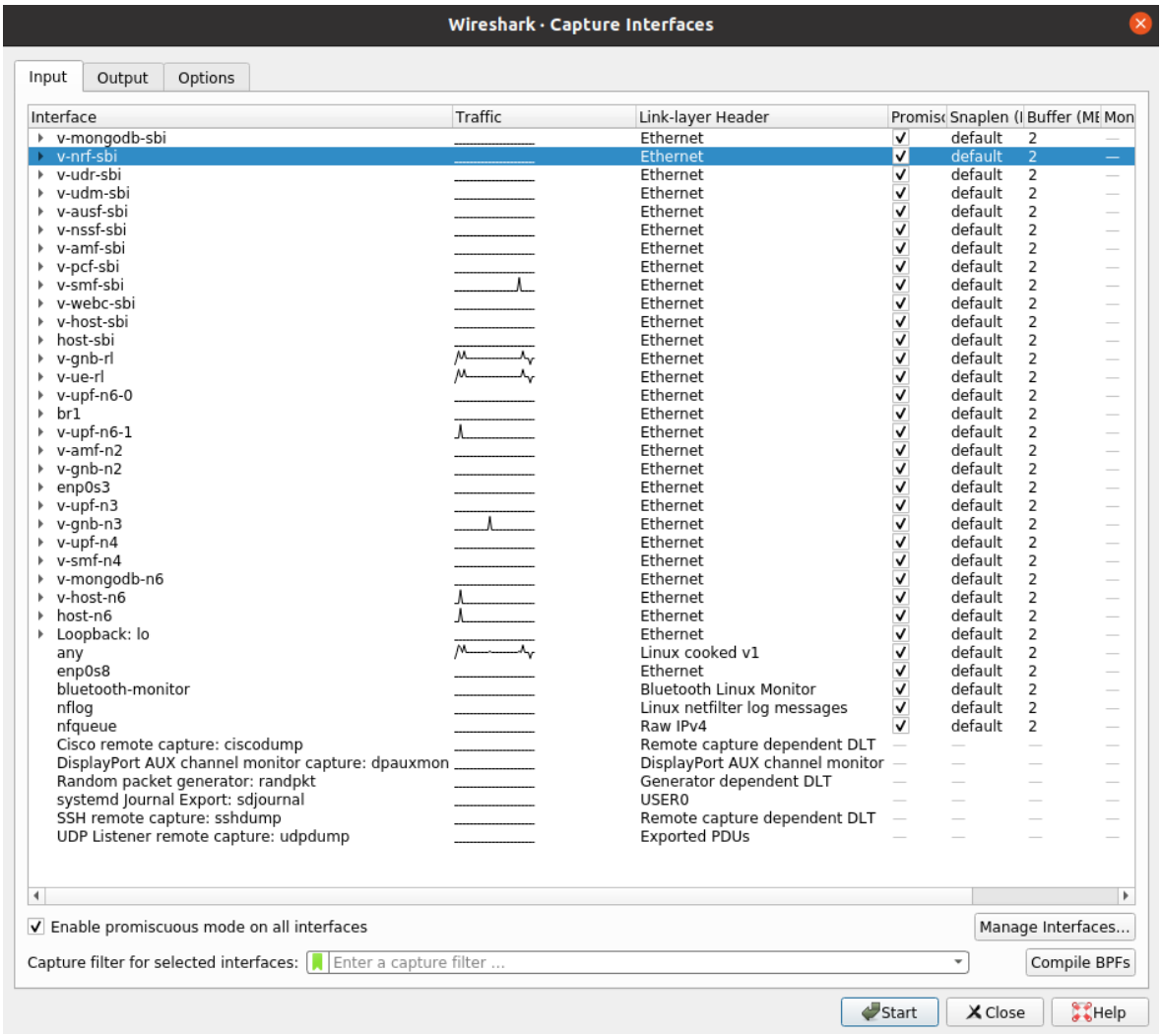



***Figure 2: Logical interfaces as seen in Wireshark, after 5G Core start***

## 1. Configurations analysis

1) Analyse the yaml configuration files in the list below (1.1.a), located in folder *~/5GLab/netns5g/config* (you may open them with the File Manager) and search for the listed configuration parameters in 1.1.b.
   a. **Files**:
      i. 5G Core: **amfcfg**.yaml, **smfcfg**.yaml, **upfcfg**.yaml
      ii. 5G RAN: free5gc-**gnb1**.yaml, free5gc-**gnb2**.yaml
      iii. 5G UEs:
         - free5gc-**ue11**.yaml
         - free5gc-**ue12**-**sl1**.yaml, free5gc-**ue12**-**sl2**.yaml
         - free5gc-**ue21**.yaml
   b. **Parameters**:
      i. MCC and MNC
         001 and ?
      ii. NR Cell Identities and TACs
         0x00000010, ? and?
      iii. Supported slices at gNB1 and gNB2 (SST+SD)
         Slice1: 0x1 and ?; Slice2: ? and 0x112233
      iv. Supported DNN
         internet
      v. List of SUPIs (UE11, UE12 and UE21)
         imsi-001010000000011, imsi-001010000000012 and imsi-001010000000021

## 2. 5GC start

1) Open a terminal window
2) Change to directory (~5GLab/netns5g) containing the scripts needed to setup and run the 5G environment
3) Initialize environment (create the namespaces and the virtual interfaces)
   ~/5GLab/netns5G$ ***sudo ./5Gsetup.sh***
   (check its contents; it enables routing, creates nat and forwarding rules, stops firewalling, and calls another script that creates the ns and links)
4) Check created namespaces and connecting links
   ~/5GLab/netns5G$ ***sudo ip netns*** – lists created namespaces
   16 namespaces, numbered 0 to 15, one for each of the components shown in the figure above, except the 'Host'
   ~/5GLab/netns5G$ ***sudo ip link*** – lists created links
   33 links are listed, numbered 0 to 57
5) Start a Wireshark capture in the interface 'br1' (this will capture all the traffic; you can start other Wireshark instances at specific interfaces, e.g. 'v-amf-sbi')
   ~/5GLab/netns5G$ ***sudo wireshark &***
6) Start the 5G Core (free5gc)
   ~/5GLab/netns5G$ ***sudo ./5Gstart.sh***

   At this point 5G Core Network Functions have started, each in its own namespace.

   Observe the script output and identify the order by which 5G Core components have been started.

   Order: NRF, UDR, UDM, AUSF, NSSF, AMF, PCF, UPF, SMF, WebUI

   Observe the successive interactions with NRF; what is that for?

   To register against the NRF (remember the NRF role)

   Related the order appear with the existing inter dependencies.
7) Stop the capture and identify the involved protocols (to facilitate it, order the capture by the 'Protocol' column by pressing the respective column top); which of those are specific 5G Core protocols?

   Protocols: ARP, HTTP2, ICMPv6, MDNS, PFCP, TCP
   5G protocols: PFCP and, indirectly, HTTP2
8) Identify the dialogs for the 5G protocols (suggestion: apply a display filter to those protocols and chech the involved entities)

   HTTP2: NRF and all the others, as origin or destination
   PFCP: SMF and UPF

## 3. gNBs start

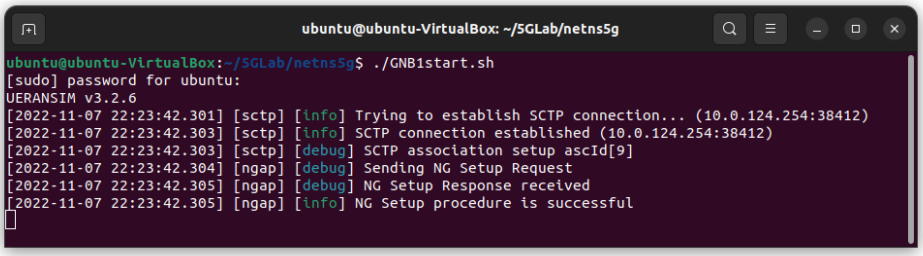
1) Open a (new) terminal window/tab
2) (re)Start Wireshark and start capturing in interface br1 (do not stop wireshark until the end of this section, step 3.7)

   $ **sudo wireshark**

   Capture -> Options -> select 'br1'

3) From the same directory, start the first gNB (gNB1)

   ~/5GLab/netns5G$ **./GNB1start.sh**




4) In the live Wireshark capture, observe/note the following:
   a. Repeat the identification of the involved protocols and the specific 5G ones

      All: ARP, NGAP, SCTP, SSL and TCP

      5G: NGAP, SCTP

   b. The SCTP connection setup and later the exchanged heartbeats (suggestion: filter the displayed packets by identified 5G protocols)
   c. Identify the involved entities

      NGAP: gNB1-N2 and AMF-N2

      SCTP: gNB1-N2 and AMF-N2

   d. Detail to the maximum extent, in the Packet Details window, the *NGsetupRequest* and *NGsetupResponse* messages (with mouse right button in '*Packet Details*', select '*Expand Subtres*'); Confirm observed values with the ones obtained from the configuration files analysis

5) Start the second gNB (gNB2)

   ~/5GLab/netns5G$ **./GNB2start.yaml**

6) In the live Wireshark compare the new *NGsetupRequest* and *NGsetupResponse* messages with previous ones (gBN1) (suggestion: apply a display filter for the NGCP protocol only and order the capture by the 'Info' column and then move the two pairs of captured packets)

   Cell identifiers and the supported slices are different between the two cells

7) Observe the logs in the screen (Core, gNB1 and gNB2) and logfiles in: ~/5GLab/netns5g/logs (suggestion: use the 'Files' application to see and open the most recent files, the ones generated until now, executing this 5G Lab)

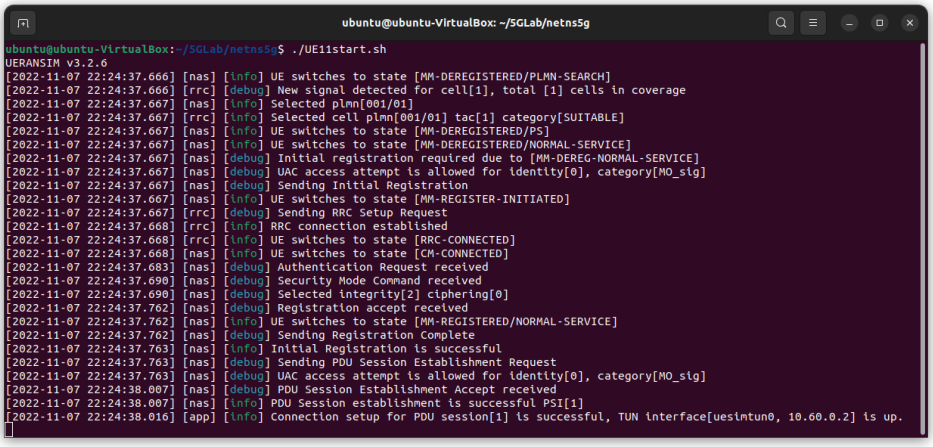
## 4. UE creation, registration and default PDU creation

1) Open the Free5GC Web Console from the web browser:
   a. ***http://10.0.123.201:5000***
   b. credentials: '***admin***'/'***free5gc***'
2) Create the 3 UEs from the table below ('***New Subscriber***'; see screen capture in the Annexes):

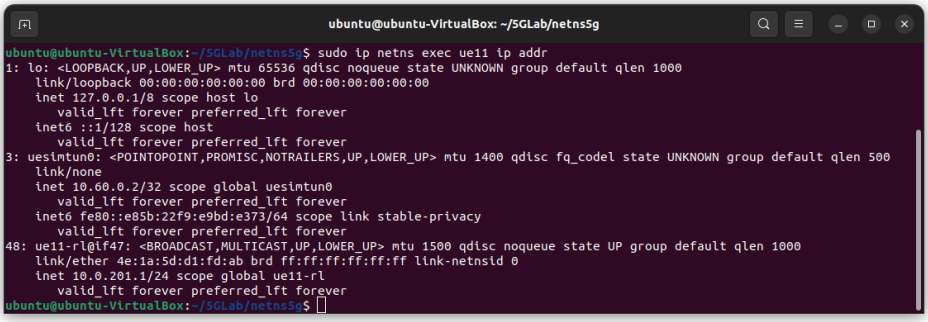
| | **UE11** | **UE12** | **UE21** |
|---|---|---|---|
| **PLMN ID (MCC/MNC)** | 00101 | 00101 | 00101 |
| **SUPI (IMSI)** | 001010000000011 | 001010000000012 | 001010000000021 |
| **SST/SD** | 1/010203 (sl1) | 1/010203 (sl1)<br>2/112233 (sl2) | 1/010203 (sl1) |
| **DNN** | internet | internet | internet |
| **UL/DL AMBR** | 10/20 Mbps | 100/200 Mbps | 1/2 Mbps |
| **5QI** | 9 | 9 | 9 |
| **Note** | Will connect to gNB1 | Will connect to gNB1 | Will connect to gNB2 |

Notes:
1) Only change the parameters shown in the table and if required
   a. do not change: Authentication method, K*, Operator Code Type, Operator Code Value*, and SQN*)
   b. you may search and interpret the other parameters.
2) In the Free5GC "New Subscriber" form, delete the second appearing S-NSSAI (*Single Network Slice Selection Assistance Information*) and the second DNN ('internet2')

3) Restart Wireshark, keeping the capture in the same interface ('br1')
4) Start the first UE (UE11)
   ~/5GLab/netns5G$ **./UE11start.yaml**




5) Observe the states the UE went through, during the process; observe the other messages and its sequence
6) Observe the creation of the new TUN interface ('uesimtun0'); in a new terminal window, you can check the creation of this interface in namespace 'ue11' and note its IP address (10.60.0.2, in the example)
   ~/5GLab/netns5G$ **sudo ip netns exec ue11 ip addr**




This interface will be used to exchange the traffic via the 5G network.

- Order the Wireshark displayed capture by 'Protocol' (press the respective column name) and list the relevant protocols

  ARP, HTTP2, HTTP2/NAS-5GS, HTTP2/NAS-5GS/NGAP, HTTP2/NGAP, NGAP, NGAP/NAS-5GS, PFCP, SCTP, SSL, SSLv2, TCP, UDP

7) Go to 'Statistics' and select 'Conversations' in Wireshark, order by 'IPv4 - 24' and enable 'Name resolution'; observe the 5G dialogs, ordering by 'Address A' and 'Address B'

8) Apply a Display Filter to see just NGAP, SCTP and PFCP protocols ("***ngap or pfcp or sctp***")
   a. Identify the involved 5G control functions (IP addresses are already translated to the functional entity interface, according to the diagram above); identify the dialogs UE-AMF, AMF-SMF, SMF-UPF and their sequence

   b. Observe the sequence of exchanged messages, looking into their details in the Packet Details window (see, for instance, the '*PFCP Session Establishment Request*' and compare with message '*PFCP Session Modification Request*')

   c. You may filter the display of messages by protocol and pair of entities, filtering the protocol and their IP addresses (e.g. for HTTP2 between AMF and AUSF: "***ip.addr==10.0.123.4 and ip.addr==10.0.123.6) and http2***")

## 5. Connectivity

1) Start a Wireshark capture in the interface 'upf-n3' and another capture in the interface 'upf-n6-0'

2) Apply a Display Filter to see protocols GTP and ICMP

3) In a terminal window, start a ping to 8.8.8.8 from UE11

   ~/5GLab/netns5G$ **sudo ip netns exec ue11 ping 8.8.8.8 -I uesimtun0**

4) Analyse, in the Wireshark Packet Details, the GTP encapsulation

   - Observe the *Tunnel Endpoint IDentifier* (TEID) in both directions of the communication

5) In a new Terminal Window/Tab, Start UE12
   ~/5GLab/netns5G$ **./UE12start-sl1.yaml**
   (check the contents of file *./config/free5gc-ue12-sl1.yaml*)

6) Make a ping from UE11 to UE12

   ~/5GLab/netns5G$ **sudo ip netns exec ue11 ping <U12 IP addr> -I uesimtun0**

   - Analyse the observed GTP packets

7) In a new Terminal Window/Tab, Start UE21
   ~/5GLab/netns5G$ **./UE12start-sl1.yaml**
   (check the contents of file *./config/free5gc-ue21.yaml*)

8) Make a ping from UE12 to UE21 and observe the exchanged packets at the UPF

## 6. QoS

1) Open a new terminal window
2) Start an iperf3 server at the DNN
   $ ***iperf3 –s***
3) Check the TUN interface name and assigned IP address
   $ **sudo ip netns exec ue11 ip addr**
4) Start an iperf3 client at UE11 towards the server instance and register the achieved bandwidth in the UL and DL directions
   $ **sudo ip netns exec ue11 iperf3 -c 10.1.0.2 -B *<ue11 IP address>*** *-- uplink*
   $ **sudo ip netns exec ue11 iperf3 -c 10.1.0.2 -R -B *<ue11 IP address>*** *-- downlink*
5) Repeat previous measurements with the other two UEs (UE12 and UE21) and compare the results

## 7. Slicing

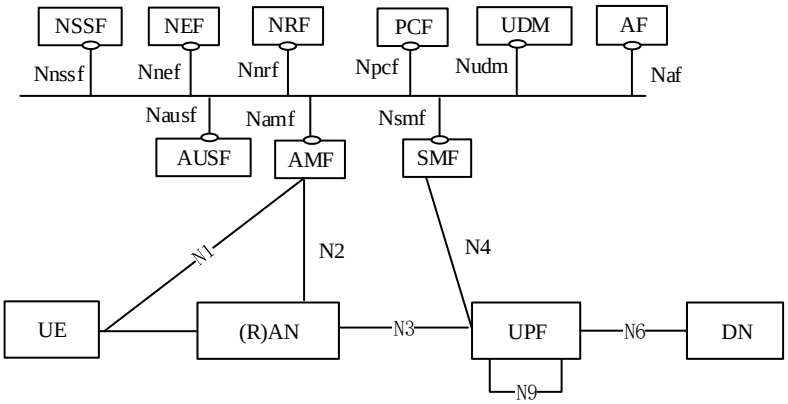
1) Stop UE12 (Ctrl-C)
2) Restart UE12, now in the second slice (2/112233) with a new configuration file and check the results
   ~/5GLab/netns5G$ **./UE12start-sl2.yaml**
   (check the contents of file *./config/free5gc-ue12-sl2.yaml*)
3) Observe the newly assigned IP address; what are the changes?
4) Make a ping from UE11 to UE12, now in different slices and observe the exchanged packets at the UPF; Is there connectivity?
   a. Check routing at the UPF namespace
      $ **sudo ip netns exec upf ip route**
   b. Add a new route in the UPF namespace
      $ **sudo ip netns exec upf ip route add 10.61.0.0./24 dev upfgtp**
5) Repeat the ping above.

## 8. Stop and reset the environment

1) Stop the the UEs, gNB nodes (Ctrl-C), and the 5G Core
2) Wait for final processes to close (this takes some seconds, ending with “NRF terminated”)
3) Delete the namespaces
   ~/5GLab/netns5G$ **sudo ./5Gcleanup.sh**

# Anexes

## A. 5G System architecture



## B. Example procedure



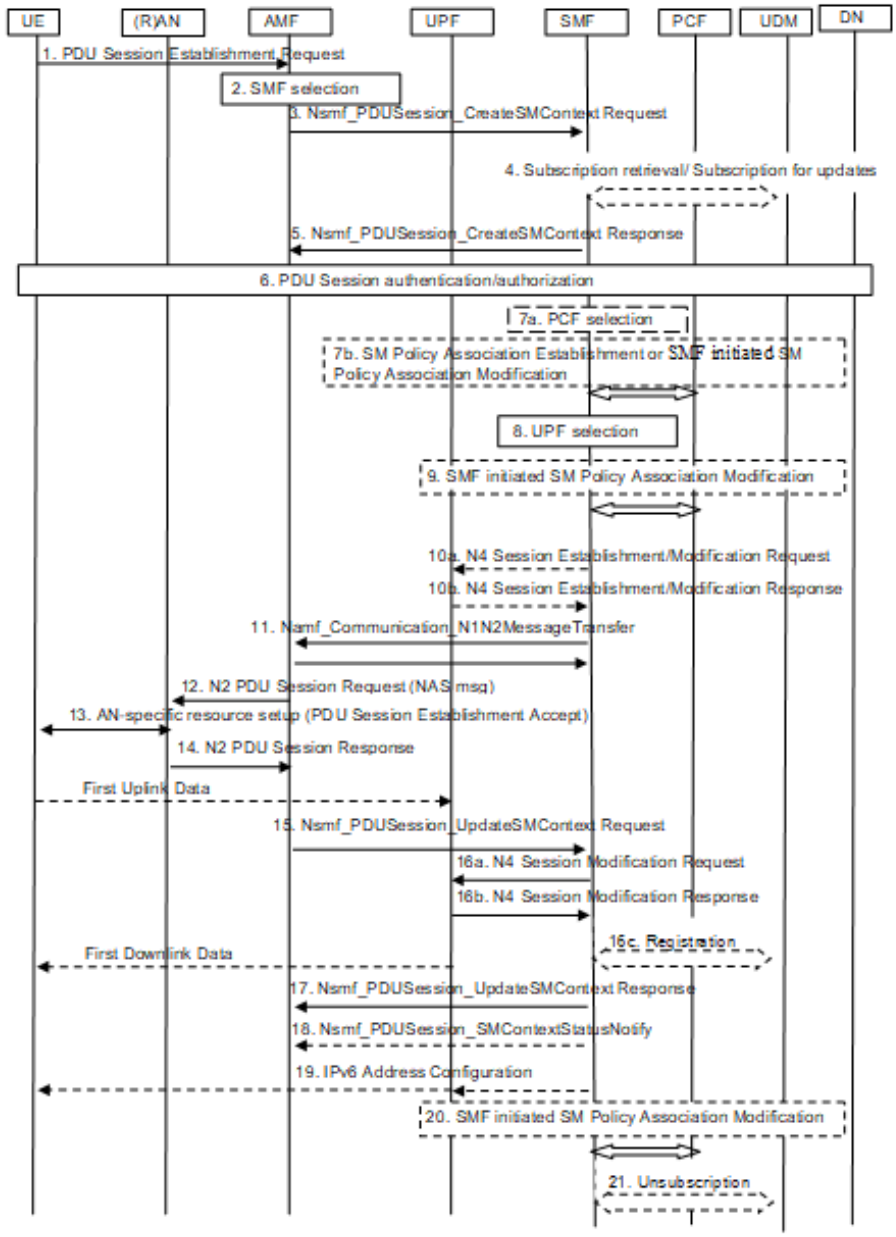
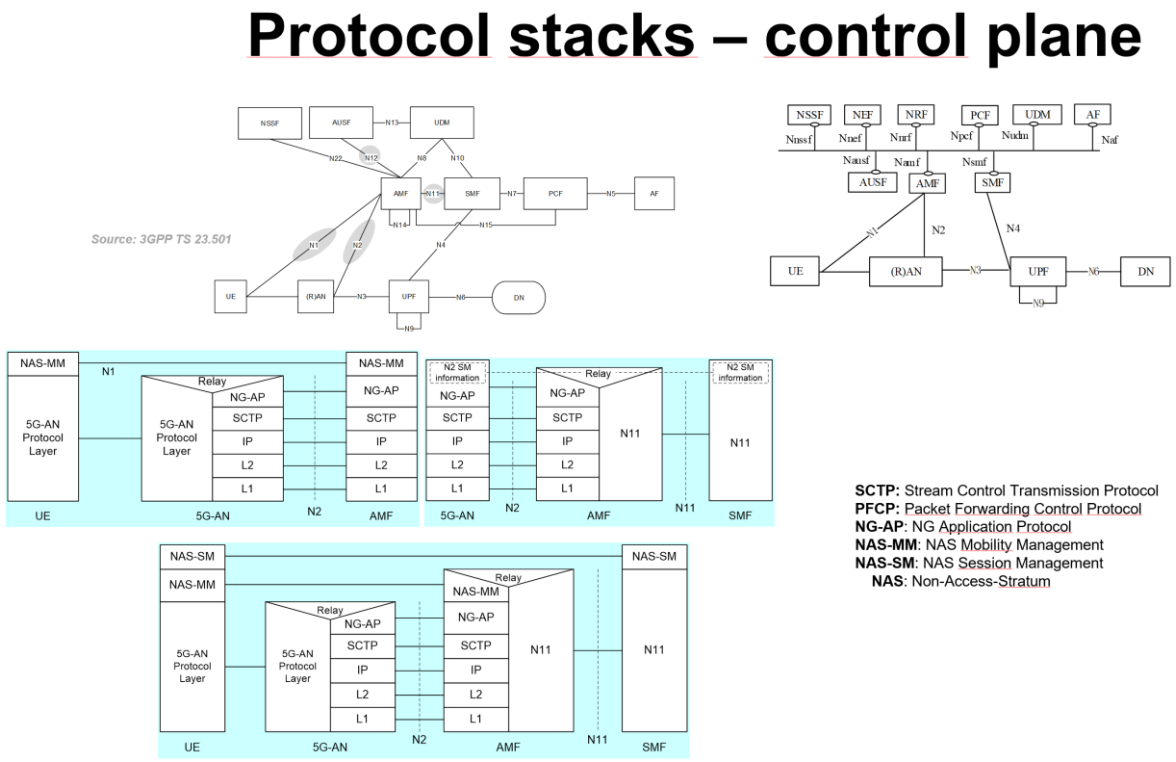
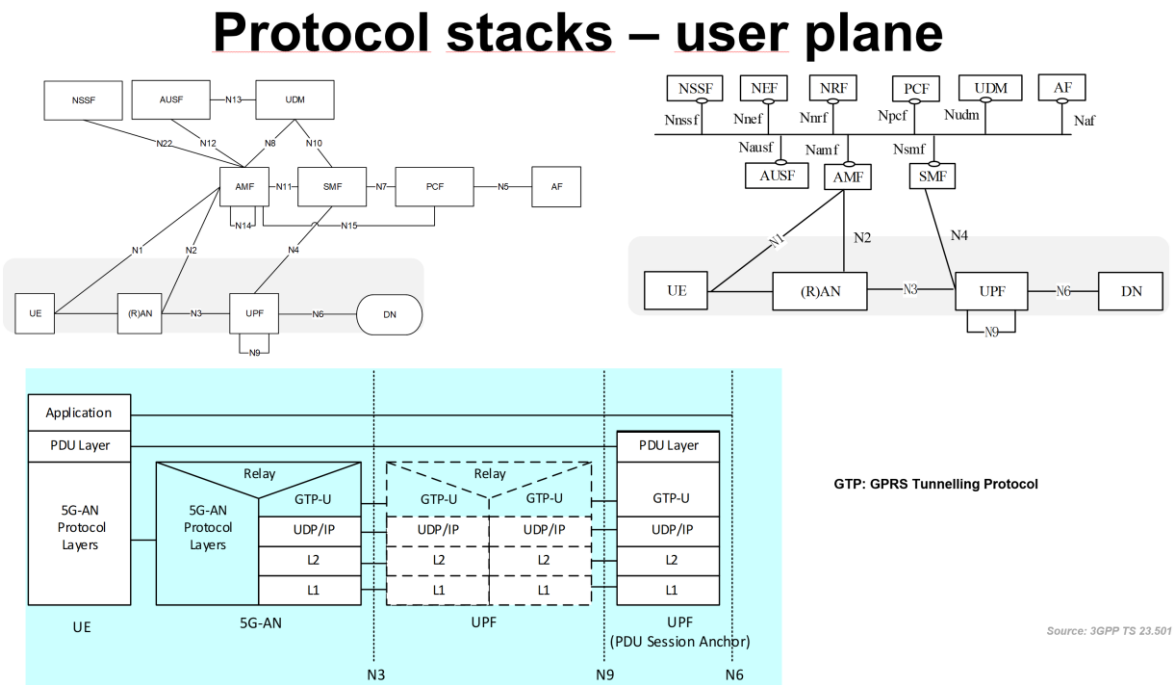


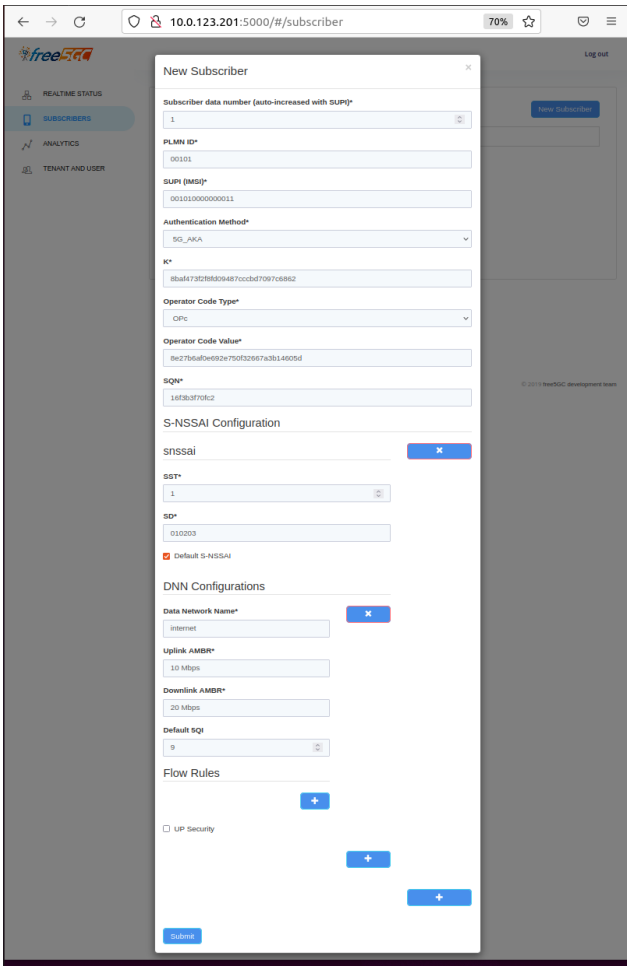

**Figure 4.3.2.2.1-1: UE-requested PDU Session Establishment for non-roaming and roaming with local breakout**

## C. 5G Protocol stacks

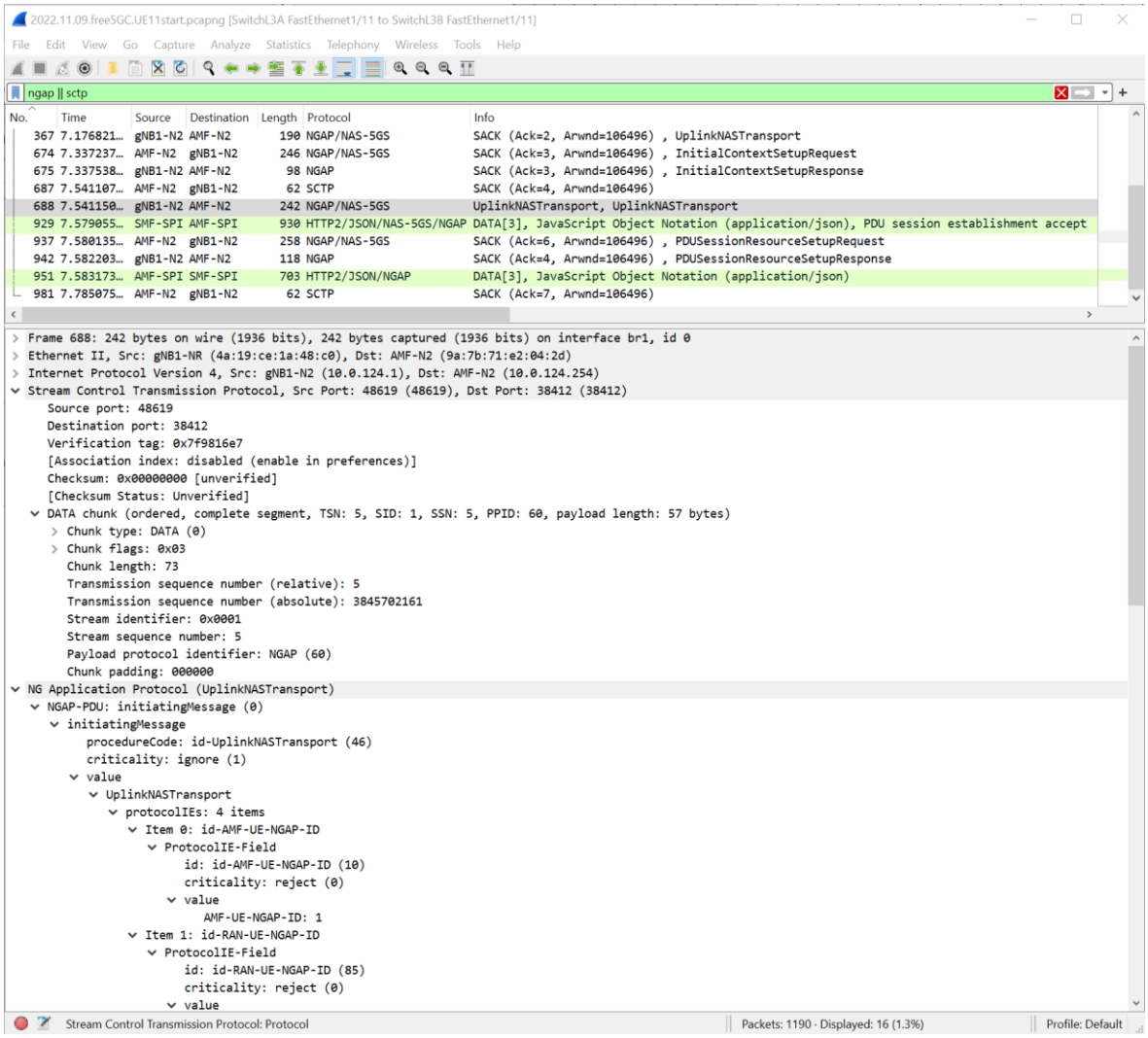


## D. Free5GC New Subscriber creation form (UE11)



## E. Example of capture with Wireshark, with addresses resolution and display filter




Wireshark · Packet 937 · 2022.11.09.freeSGC.UE11start.pcapng
Frame 937: 258 bytes on wire (2064 bits), 258 bytes captured (2064 bits) on interface br1, id 0
Ethernet II, Src: AMF-N2 (9a:7b:71:e2:04:2d), Dst: gNB1-NR (4a:19:ce:1a:48:c0)
Internet Protocol Version 4, Src: AMF-N2 (10.0.124.254), Dst: gNB1-N2 (10.0.124.1)
Stream Control Transmission Protocol, Src Port: 38412 (38412), Dst Port: 48619 (48619)
NG Application Protocol (PDUSessionResourceSetupRequest)
NGAP-PDU: initiatingMessage (0)
initiatingMessage
procedureCode: id-PDUSessionResourceSetup (29)
criticality: reject (0)
value
PDUSessionResourceSetupRequest
protocolIEs: 4 items
Item 0: id-AMF-UE-NGAP-ID
ProtocolIE-Field
id: id-AMF-UE-NGAP-ID (10)
criticality: reject (0)
value
AMF-UE-NGAP-ID: 1
Item 1: id-RAN-UE-NGAP-ID
ProtocolIE-Field
id: id-RAN-UE-NGAP-ID (85)
criticality: reject (0)
value
RAN-UE-NGAP-ID: 1
Item 2: id-PDUSessionResourceSetupListSUReq
ProtocolIE-Field
id: id-PDUSessionResourceSetupListSUReq (74)
criticality: reject (0)
value
PDUSessionResourceSetupListSUReq: 1 item
Item 0
PDUSessionResourceSetupItemSUReq
pDUSessionID: 1
pDUSessionNAS-PDU: 7e02cad24c2a027e00680100432e0101c2110009010006313101ff090606001406000a…
Non-Access-Stratum 5GS (NAS)PDU
Security protected NAS 5GS message
Extended protocol discriminator: 5G mobility management messages (126)
0000 .... = Spare Half Octet: 0
.... 0010 = Security header type: Integrity protected and ciphered (2)
Message authentication code: 0xcad24c2a
Sequence number: 2
Encrypted data
s-NSSAI
sST: 01
sD: 010203
pDUSessionResourceSetupRequestTransfer: 000004008200090c01312d0020989680008b000a01f00a0082fe0000000100860001000…
PDUSessionResourceSetupRequestTransfer
protocolIEs: 4 items
Item 0: id-PDUSessionAggregateMaximumBitRate
ProtocolIE-Field
id: id-PDUSessionAggregateMaximumBitRate (130)
criticality: reject (0)
value
PDUSessionAggregateMaximumBitRate
pDUSessionAggregateMaximumBitRateDL: 20000000bits/s
pDUSessionAggregateMaximumBitRateUL: 10000000bits/s
Item 1: id-UL-NGU-UP-TNLInformation
ProtocolIE-Field
id: id-UL-NGU-UP-TNLInformation (139)
criticality: reject (0)
value
UPTransportLayerInformation: gTPTunnel (0)
gTPTunnel
transportLayerAddress: 0a0082fe [bit length 32, 0000 1010 0000 0000 1000 0010 1111 1110 decimal value 167805694]
TransportLayerAddress (IPv4): 10.0.130.254 (10.0.130.254)
gTP-TEID: 00000001
Item 2: id-PDUSessionType
ProtocolIE-Field
id: id-PDUSessionType (134)
criticality: reject (0)
value
PDUSessionType: ipv4 (0)
Item 3: id-QosFlowSetupRequestList
ProtocolIE-Field
id: id-QosFlowSetupRequestList (136)
criticality: reject (0)
value
QosFlowSetupRequestList: 1 item
Item 0
QosFlowSetupRequestItem
qosFlowIdentifier: 9
qosFlowLevelQosParameters
qosCharacteristics: nonDynamic5QI (0)
nonDynamic5QI
fiveQI: 9
allocationAndRetentionPriority
priorityLevelARP: 15
pre-emptionCapability: shall-not-trigger-pre-emption (0)
pre-emptionVulnerability: not-pre-emptable (0)
Item 3: id-UEAggregateMaximumBitRate
ProtocolIE-Field
id: id-UEAggregateMaximumBitRate (110)
criticality: ignore (1)
value
UEAggregateMaximumBitRate
uEAggregateMaximumBitRateDL: 2000000000bits/s
uEAggregateMaximumBitRateUL: 1000000000bits/s
Show packet bytes
Close
Help

## F. Hosts file

```
#5G Core
10.0.123.1          NRF-SBI
10.0.123.2          UDR-SBI
10.0.123.3          UDM-SBI
10.0.123.4          AUSF-SBI
10.0.123.5          NSSF-SBI
10.0.123.6          AMF-SBI
10.0.123.7          PCF-SBI
10.0.123.9          SMF-SBI
10.0.123.100        MongoDB-SBI
10.0.123.201        WebConsole

10.0.124.254        AMF-N2
10.0.124.1          gNB1-N2
10.0.124.2          gNB2-N2

10.0.140.2          SMF-N4
10.0.140.1          UPF-N4

#5G dataplane
10.1.0.1            UPF-N6
10.1.0.1            Host-N6

#RAN1
10.0.201.1          UE11-NR
10.0.201.2          UE12-NR
10.0.201.254        gNB1-NR

#RAN2
10.0.202.1          UE11-NR
10.0.202.254        gNB1-NR
```

## G. Useful links

- Free5GC:
  - [free5Gcore] https://www.free5gc.org/
  - [free5gcwiki] https://github.com/free5gc/free5gc/wiki
  - [konrad] https://github.com/konradkar2/netns5g
- UERANSIM:
  - [ueransim] https://github.com/aligungr/UERANSIM/wiki
- 3GPP
  - [3gpp] https://www.3gpp.org