LTE Network Simulation

Mobile Network Communication Systems - KPM

Assignment 05

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1. Description of network scenario:

```
/* ---------------------------- SIMULATION SCENARIO ----------------------------
 *
 *                           +-----------------------+
 *                           |      Remote Host      |
 *                           +-----------------------+
 *                               1.0.0.1 |
 *                                       | Point-to-Point
 *                                       |
 *                               1.0.0.2 v
 *                           +-----------------------+
 *                           |         P-GW          |
 *                           +-----------------------+
 *                              14.0.0.5 |
 *                                       | S5 interface
 *                              14.0.0.6 |
 *                           +-----------------------+ 13.0.0.6    13.0.0.5 +----------------------+
 *                           |         S-GW          |----------------------|         MME          |
 *                           +-----------------------+     S11 interface     +----------------------+
 *                                       |
 *                                       | S1 interface
 *                                       |
 *                       +---------------+----------------+
 *                       |                                |
 *                       v                                v
 *           +-----------------------+        +-----------------------+
 *           |   eNodeB 0 10.0.0.5   |        |   eNodeB 1 10.0.0.9   |
 *           +-----------------------+        +-----------------------+
 *                       |                                |
 *                       | LTE                            | LTE
 *                       v                                v
 *              +------------------+             +------------------+
 *              |   UE 0 7.0.0.2   |             |   UE 1 7.0.0.3   |
 *              +------------------+             +------------------+
 *              +------------------+             +------------------+
 *              |   UE 2 7.0.0.4   |             |   UE 3 7.0.0.5   |
 *              +------------------+             +------------------+
 *              +------------------+
 *              |   UE 4 7.0.0.6   |
 *              +------------------+
 */
```

This document dives into the simulation of an LTE network, providing an immersive explanation of its design and operation. Designed for students delving into telecommunications, the scenario merges theoretical LTE concepts with practical simulation techniques, offering a robust platform for mastering network analysis.

Components of the Network

The network's core revolves around a well-defined hierarchy of components, each serving a critical function. At the top, a **Remote Host** plays the role of an external server, delivering video streams to user devices. This host connects to the LTE network via a high-speed Point-to-Point link. Such specifications emulate modern backbone connections, forming the foundation of the simulation.

Within the LTE core, two central nodes take charge: the **Packet Gateway (P-GW)** and the **Serving Gateway (S-GW)**. The P-GW bridges the LTE domain with external IP networks, ensuring smooth routing of packets to and from the Remote Host. Meanwhile, the S-GW complements its efforts by managing traffic between the base stations (eNodeBs) and the LTE core. Together, these gateways exemplify the intricate mechanics of modern telecommunications systems.

Mobility and session control fall under the jurisdiction of the **Mobility Management Entity (MME)**. This node ensures seamless connectivity for User Equipments (UEs), dynamically adjusting to their movements. Its role is pivotal, particularly during handovers between base stations, where it maintains session continuity and minimizes disruptions.

The LTE access layer comprises two static **eNodeBs**, strategically positioned to maximize coverage and minimize interference. These base stations establish the primary connection to the UEs, managing radio resources and scheduling traffic to ensure consistent performance. Their grid-based layout reflects real-world deployment strategies, further grounding the simulation in reality.
At the edge of the network, five **User Equipments (UEs)** bring the scenario to life. These mobile devices engage in two primary activities: file transfers over TCP and video streaming via UDP. Their dynamic movement, governed by the RandomWalk2d mobility model, introduces variability and challenges that mimic urban pedestrian behavior.

Simulation Workflow

The simulation's workflow begins with node initialization. Each entity—Remote Host, eNodeBs, and UEs—is configured with distinct roles and integrated into the topology. Mobility models dictate the movement of UEs, while static nodes remain fixed to represent real-world infrastructure. Following this, traffic flows are established, with TCP supporting file transfers and UDP enabling video streams. These applications simulate common user scenarios, from collaborative work to entertainment.

Performance Evaluation

Throughout the simulation, performance metrics are meticulously tracked using the FlowMonitor module. Key data points—throughput, latency, jitter, and packet loss—are collected, offering a comprehensive view of the network's behavior. Results are exported to CSV files, providing a foundation for detailed analysis and visualization.

2. Configuration settings, including LTE and application parameters:

The LTE simulation is structured around a set of meticulously defined configuration parameters, ensuring realistic performance and accurate emulation of a real-world network. These settings are tailored to represent common scenarios in telecommunications, balancing complexity and usability.

LTE Configuration

The LTE settings in this simulation are designed to capture the essence of a modern network:

1. **Bandwidth and Frequency:**
   - The channel bandwidth is defined by default in the NS-3 LTE model, typically set to 20 MHz, which aligns with standard LTE deployment scenarios.

2. **Transmission Power:**
   - Transmission power for eNodeBs is set to default NS-3 values unless modified explicitly in the script. Typically, eNodeBs operate at 46 dBm in simulations, ensuring robust signal strength.

3. **Scheduling and Resource Allocation:**
   - The NS-3 LTE model uses Proportional Fair scheduling by default for resource allocation, balancing throughput and fairness across UEs.

4. **Handover Mechanisms:**
   - Handover mechanisms are enabled in the NS-3 LTE model, allowing UEs to transition between eNodeBs seamlessly.

Application Parameters

The script project.py defines multiple simulation scenarios with diverse configurations for traffic and network conditions. Key parameters include:

1. **Backbone Connection:**
   - Bandwidth ranges from 500 Mbps to 50 Gbps.
   - Delay values vary from 1 ms to 200 ms.

2. **UE File Transfer Data Rate:**
   - The data rate for peer-to-peer file transfers between UEs is scenario-dependent, with values ranging from 500 Kbps to 10 Mbps.

3. **Video Streaming Data Rate:**
   - Configurations include a variety of video streaming bitrates, ranging from 2 Mbps to 20 Mbps.

4. **Simulation Duration:**
   - Each scenario runs for a total of 10 seconds, providing sufficient time to analyze network behavior across different setups.

5. **Mobility Models:**
    - UEs move dynamically within a bounded area of 100x100 meters using the RandomWalk2d model, introducing topological variations.
    - eNodeBs remain stationary, reflecting their role as fixed infrastructure.

Example Scenarios

Some example scenarios (0-9) defined in project.py include:

Scenario 6:

- Backbone Bandwidth: 500 Mbps, Delay: 100 ms
- UE File Transfer Rate: 5 Mbps
- Video Streaming Rate: 10 Mbps

Scenario 3:

- Backbone Bandwidth: 1 Gbps, Delay: 50 ms
- UE File Transfer Rate: 2 Mbps
- Video Streaming Rate: 5 Mbps

Scenario 5:

- Backbone Bandwidth: 50 Gbps, Delay: 1 ms
- UE File Transfer Rate: 1 Mbps
- Video Streaming Rate: 2 Mbps

3. Results and analysis of network performance:

The results of this simulation provide critical insights into the performance of the LTE network under varying configurations. By analyzing metrics such as throughput, latency, jitter, and packet loss, we aim to evaluate the efficiency and reliability of the simulated network. Each scenario reveals unique characteristics influenced by the specified backbone speeds, delays, and application data rates.

This section will summarize the collected data, highlight key performance trends, and offer an in-depth interpretation of the results to understand how different parameters impact the overall network behavior.

There are 10 + 1 scenarios; the last one is dedicated to testing long-term stability. The remaining ten scenarios are designed for comparative analysis of varying network configurations.esults of this simulation provide critical insights into the performance of the LTE network under varying configurations. By analyzing metrics such as throughput, latency, jitter, and packet loss, we aim to evaluate the efficiency and reliability of the simulated network. Each scenario reveals unique characteristics influenced by the specified backbone speeds, delays, and application data rates.

This section will summarize the collected data, highlight key performance trends, and offer an in-depth interpretation of the results to understand how different parameters impact the overall network behavior.

Table of Parameters for All Scenarios:

Scenario	Backbone Bandwidth	Backbone Delay	UE File Transfer Rate	Video Streaming Rate
Scenario 0	10 Gbps	5 ms	5 Mbps	10 Mbps
Scenario 1	20 Gbps	2 ms	1 Mbps	5 Mbps
Scenario 2	10 Gbps	10 ms	10 Mbps	20 Mbps
Scenario 3	1 Gbps	50 ms	2 Mbps	5 Mbps
Scenario 4	5 Gbps	5 ms	500 Kbps	15 Mbps
Scenario 5	50 Gbps	1 ms	1 Mbps	2 Mbps
Scenario 6	500 Mbps	100 ms	5 Mbps	10 Mbps
Scenario 7	5 Gbps	10 ms	3 Mbps	8 Mbps
Scenario 8	1 Gbps	200 ms	1 Mbps	2 Mbps
Scenario 9	10 Gbps	10 ms	5 Mbps	10 Mbps
Stability Test	10 Gbps	5 ms	5 Mbps	10 Mbps

Table of adresses:

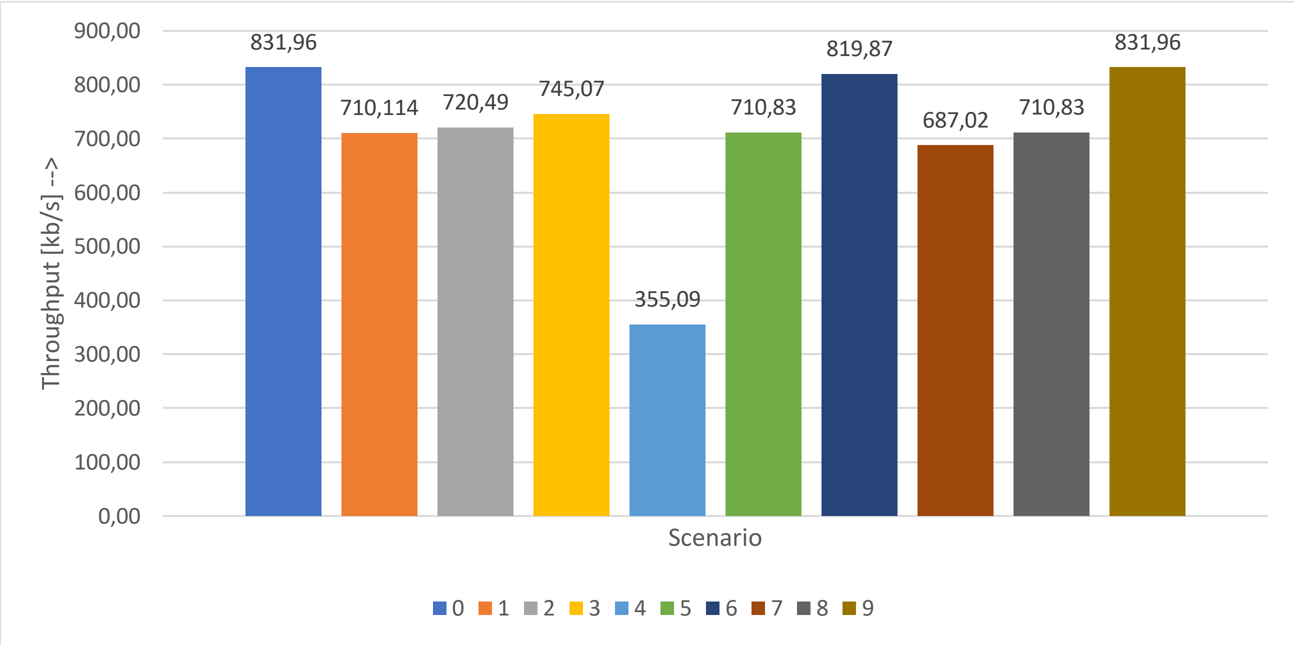
Remote host address:	1.0.0.1
P-GW address:	1.0.0.2
UE 0 IP Address:	7.0.0.2
UE 1 IP Address:	7.0.0.3
UE 2 IP Address:	7.0.0.4
UE 3 IP Address:	7.0.0.5
UE 4 IP Address:	7.0.0.6
Attached UE 0 to eNodeB 0	
Attached UE 1 to eNodeB 1	
Attached UE 2 to eNodeB 0	
Attached UE 3 to eNodeB 1	
Attached UE 4 to eNodeB 0	

Comparison Table for All Scenarios for Flow 6:

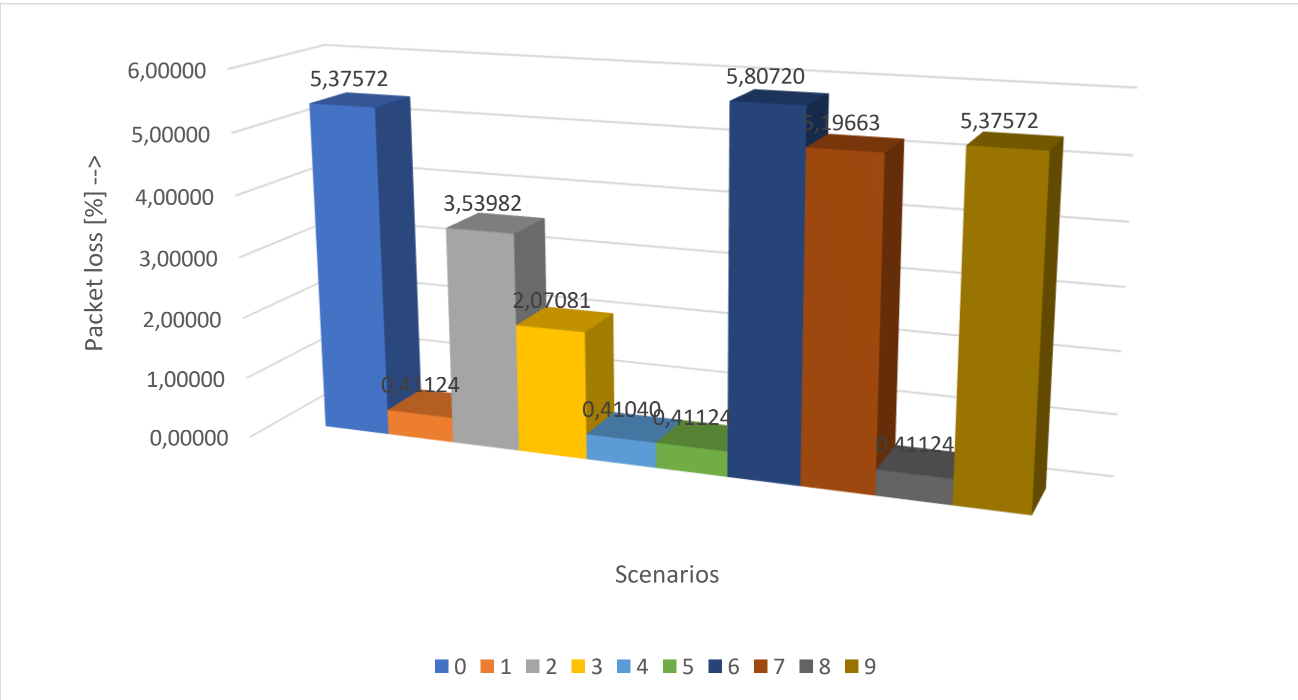
Scenario:	0	1	2	3	4
Flow ID:	6	6	6	6	6
Src address:	7.0.0.3	7.0.0.3	7.0.0.3	7.0.0.3	7.0.0.3
Dst address:	7.0.0.2	7.0.0.2	7.0.0.2	7.0.0.2	7.0.0.2
Src port:	49153	49153	49153	49153	49153
Dst port:	4000	4000	4000	4000	4000
Tx Packets/Bytes:	1730/1007216	1459/820836	1469/859564	1497/874188	731/410244
Rx Packets/Bytes:	1637/953304	1453/817960	1417/829544	1466/856796	728/409060
Throughput:	831.958 kb/s	710.114 kb/s	720.491 kb/s	745.071 kb/s	355.087 kb/s
Delay sum:	35162 ms	20935 ms	33718 ms	33283 ms	13252 ms
Mean delay:	21.4796 ms	14.4087 ms	23.7955 ms	22.7033 ms	18.2038 ms
Jitter sum:	2535 ms	4274 ms	2433 ms	2431 ms	3750 ms
Mean jitter:	1.54973 ms	2.94411 ms	1.71828 ms	1.65967 ms	5.15925 ms
Lost Packets:	93	6	52	31	3
Packet loss:	5.37572 %	0.411241 %	3.53982 %	2.07081 %	0.410397 %

Scenario:	5	6	7	8	9
Flow ID:	6	6	6	6	6
Src address:	7.0.0.3	7.0.0.3	7.0.0.3	7.0.0.3	7.0.0.3
Dst address:	7.0.0.2	7.0.0.2	7.0.0.2	7.0.0.2	7.0.0.2
Src port:	49153	49153	49153	49153	49153
Dst port:	4000	4000	4000	4000	4000
Tx Packets/Bytes:	1459/820836	1722/1002512	1424/834432	1459/820836	1730/1007216
Rx Packets/Bytes:	1453/817960	1622/944484	1350/791452	1453/817960	1637/953304
Throughput:	710.825 kb/s	819.865 kb/s	687.024 kb/s	710.825 kb/s	831.958 kb/s
Delay sum:	20888 ms	35539 ms	31813 ms	20882 ms	35162 ms
Mean delay:	14.3764 ms	21.9107 ms	23.5658 ms	14.3722 ms	21.4796 ms
Jitter sum:	4245 ms	2711 ms	2246 ms	4292 ms	2535 ms
Mean jitter:	2.92361 ms	1.67265 ms	1.66534 ms	2.95621 ms	1.54973 ms
Lost Packets:	6	100	74	6	93
Packet loss:	0.411241 %	5.8072 %	5.19663 %	0.411241 %	5.37572 %

Graphical Representation of Throughput:



Graphical Representation of Packet Loss:

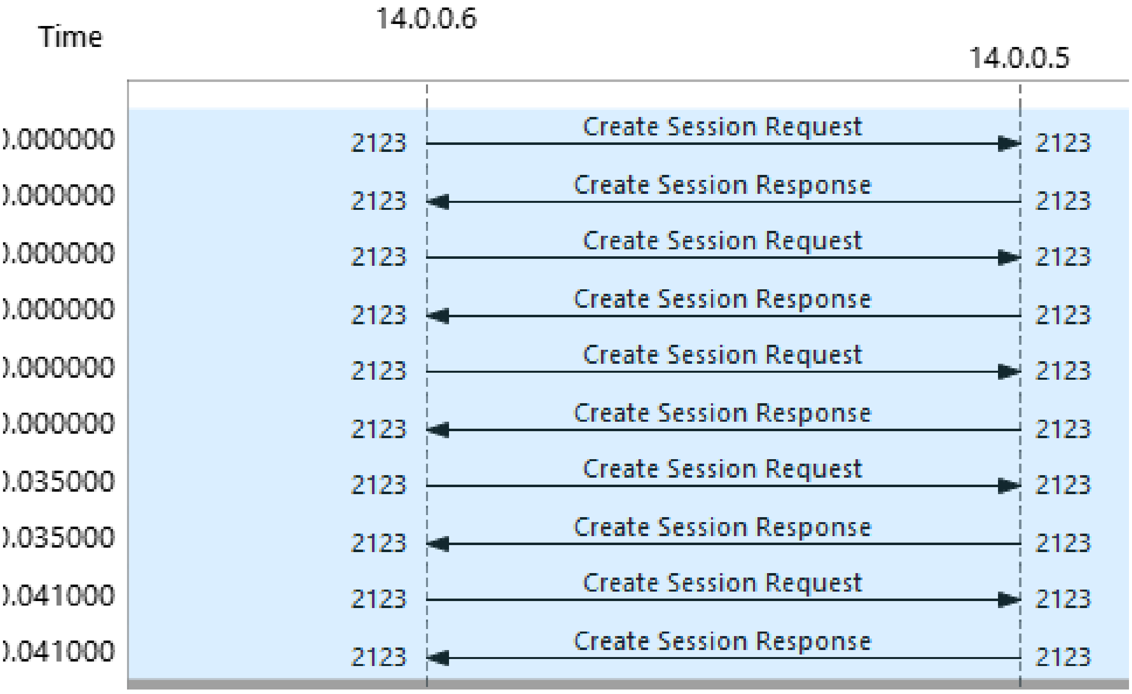


Here is sample of wireshark catched comunication in scenario 6:

Summary of Observed Communication
This packet trace involves multiple protocols (GTPv2, TCP, UDP/GTP, and ICMP), each serving distinct purposes in the LTE network simulation. Here's how they interact and function within the network:

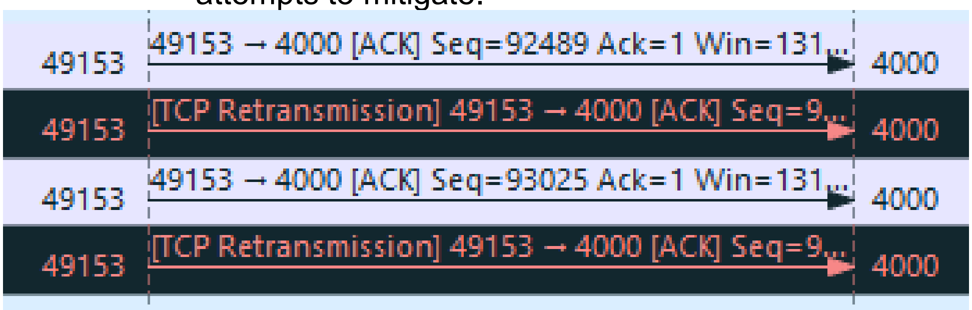
a) GTPv2 Communication: Control Plane

- GTPv2 is used for signaling and session management in the LTE control plane.
  - Packets like Create Session Request and Create Session Response demonstrate the establishment of sessions between nodes 14.0.0.6 and 14.0.0.5. The control plane setup establishes logical tunnels for user-plane data transfer, which later involves GTP encapsulation for application data.



b) GTP with TCP Encapsulation: User Plane

- GTP encapsulates TCP data in the user plane for reliable end-to-end communication.
  - TCP packets (e.g., SYN and ACK messages) are encapsulated within GTP for transport between nodes 7.0.0.3 and 7.0.0.2. Retransmissions and duplicate ACKs indicate potential packet loss or delays, which TCP attempts to mitigate.



GTP <TCP>: 49153 → 4000 [ACK] Seq=92489 Ack=1 Win=.

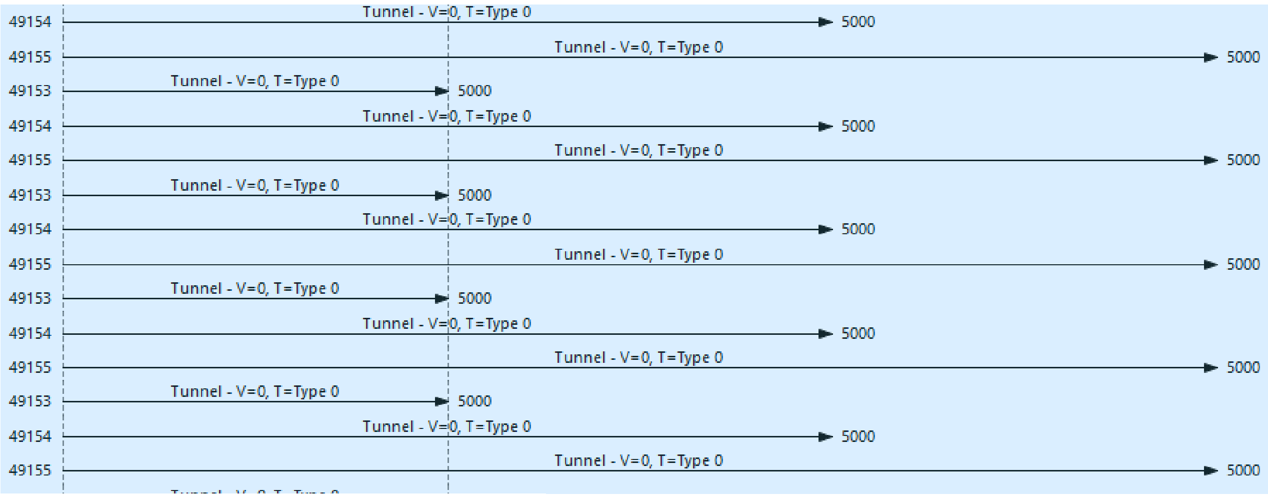
GTP <TCP>: [TCP Retransmission] 49153 → 4000 [ACK] Se...

GTP <TCP>: 49153 → 4000 [ACK] Seq=93025 Ack=1 Win=.

GTP <TCP>: [TCP Retransmission] 49153 → 4000 [ACK] Se...

c) GTP with TAPA Encapsulation

- TAPA (Tunnel Application Payload Adapter) encapsulates application-layer traffic for user-plane transport.
    - GTP <TAPA> packets carry payload data between 1.0.0.1 and nodes 7.0.0.x. These represent tunneled application-level communications, typical for video streaming or file transfers in an LTE network.
    -



GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

GTP <TAPA>: Tunnel - V=0, T=Type 0

d) ICMP Communication: Error Reporting

- ICMP (Internet Control Message Protocol) provides error feedback for unreachable destinations or other issues.
    - ICMP packets report Destination unreachable (Port unreachable) errors, suggesting either configuration issues or unavailability of the destination nodes.

GTP <ICMP>: Destination unreachable (Port unreachable)

GTP <ICMP>: Destination unreachable (Port unreachable)

GTP <ICMP>: Destination unreachable (Port unreachable)

GTP <ICMP>: Destination unreachable (Port unreachable)

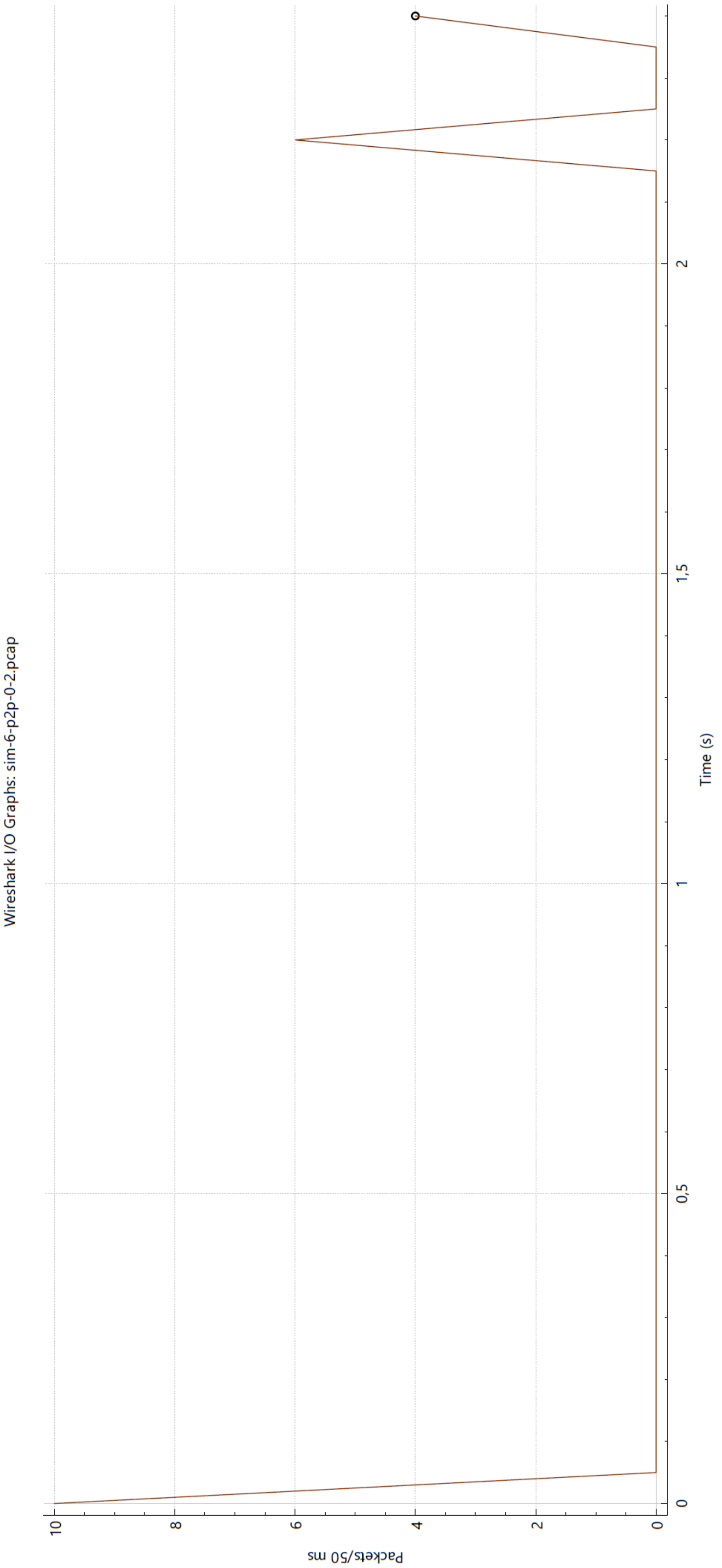
GTP <ICMP>: Destination unreachable (Port unreachable)

GTP <ICMP>: Destination unreachable (Port unreachable)

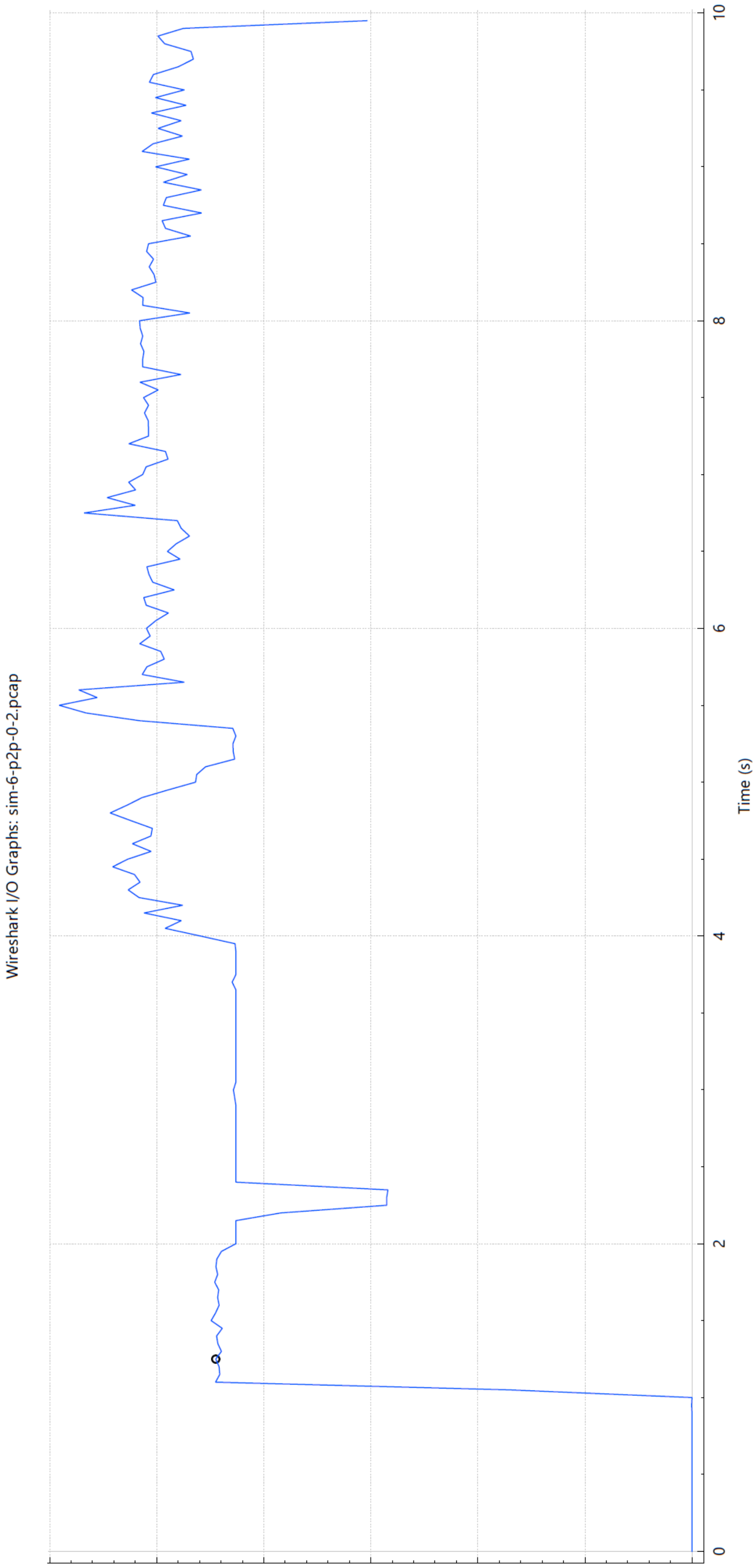
GTP <ICMP>: Destination unreachable (Port unreachable)

GTP <ICMP>: Destination unreachable (Port unreachable)

Flow graphs:
GTPv2:

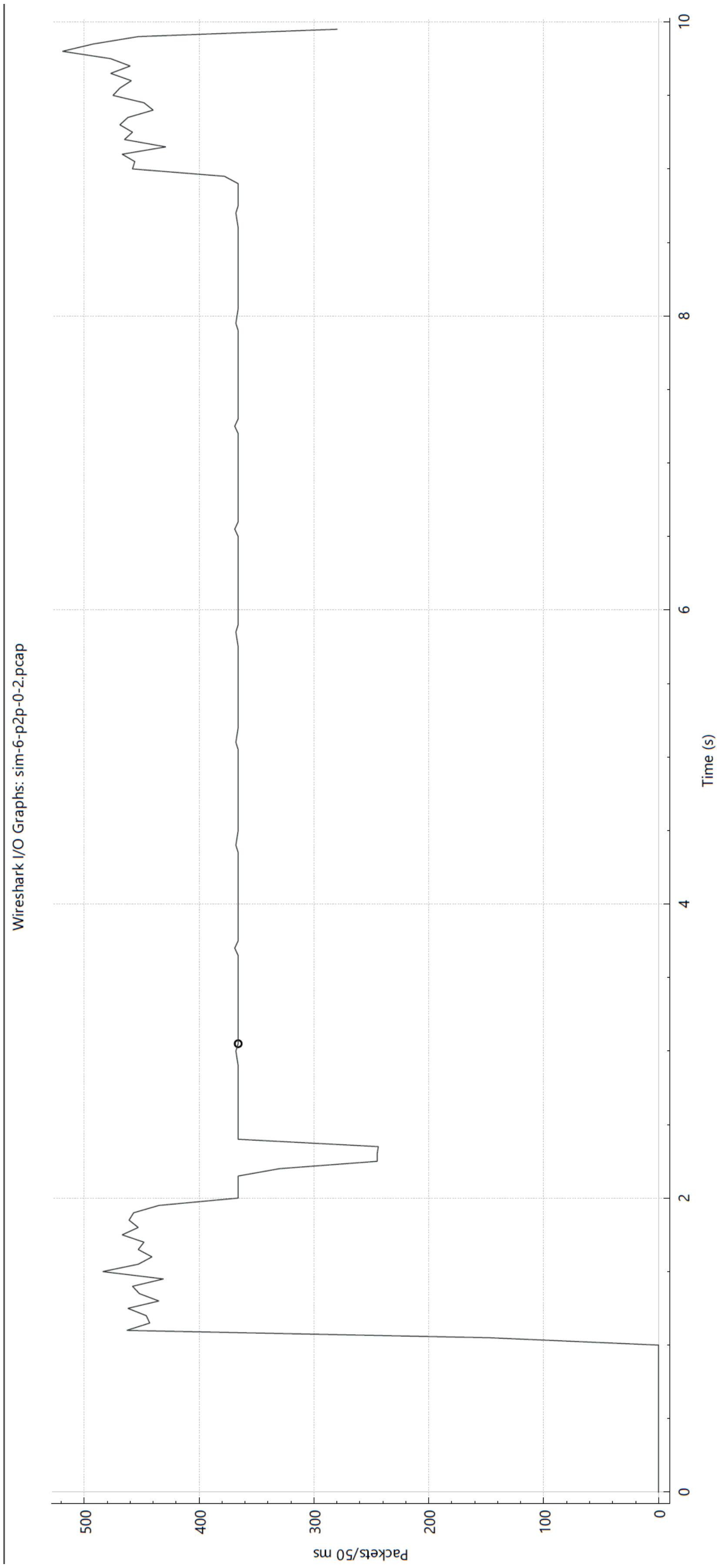


GTP:



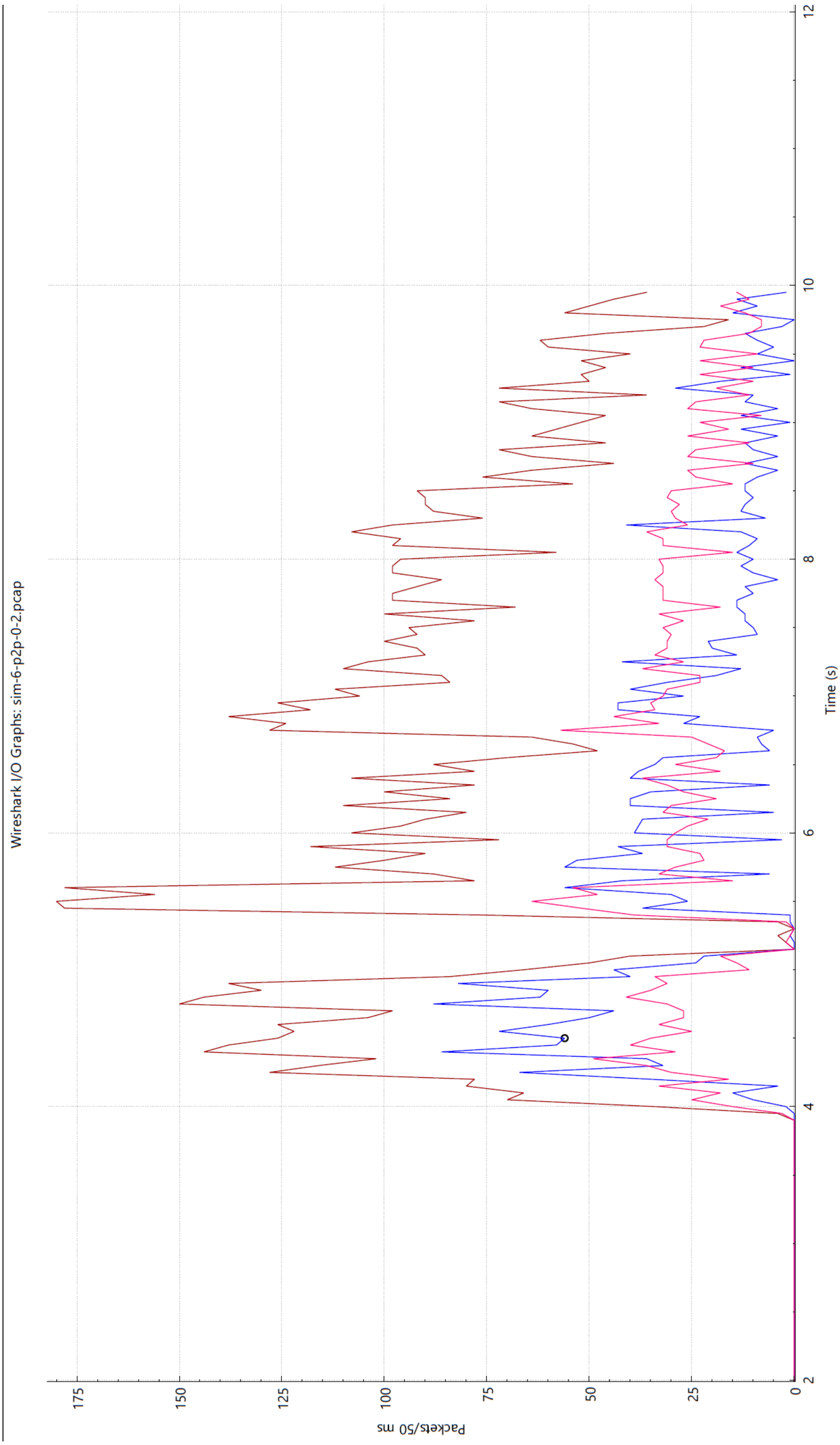
Wireshark I/O Graphs: sim-6-p2p-0-2.pcap
Bytes/50 ms
300000
250000
200000
150000
100000
50000
0
Time (s)
0
2
4
6
8
10

TAPA:

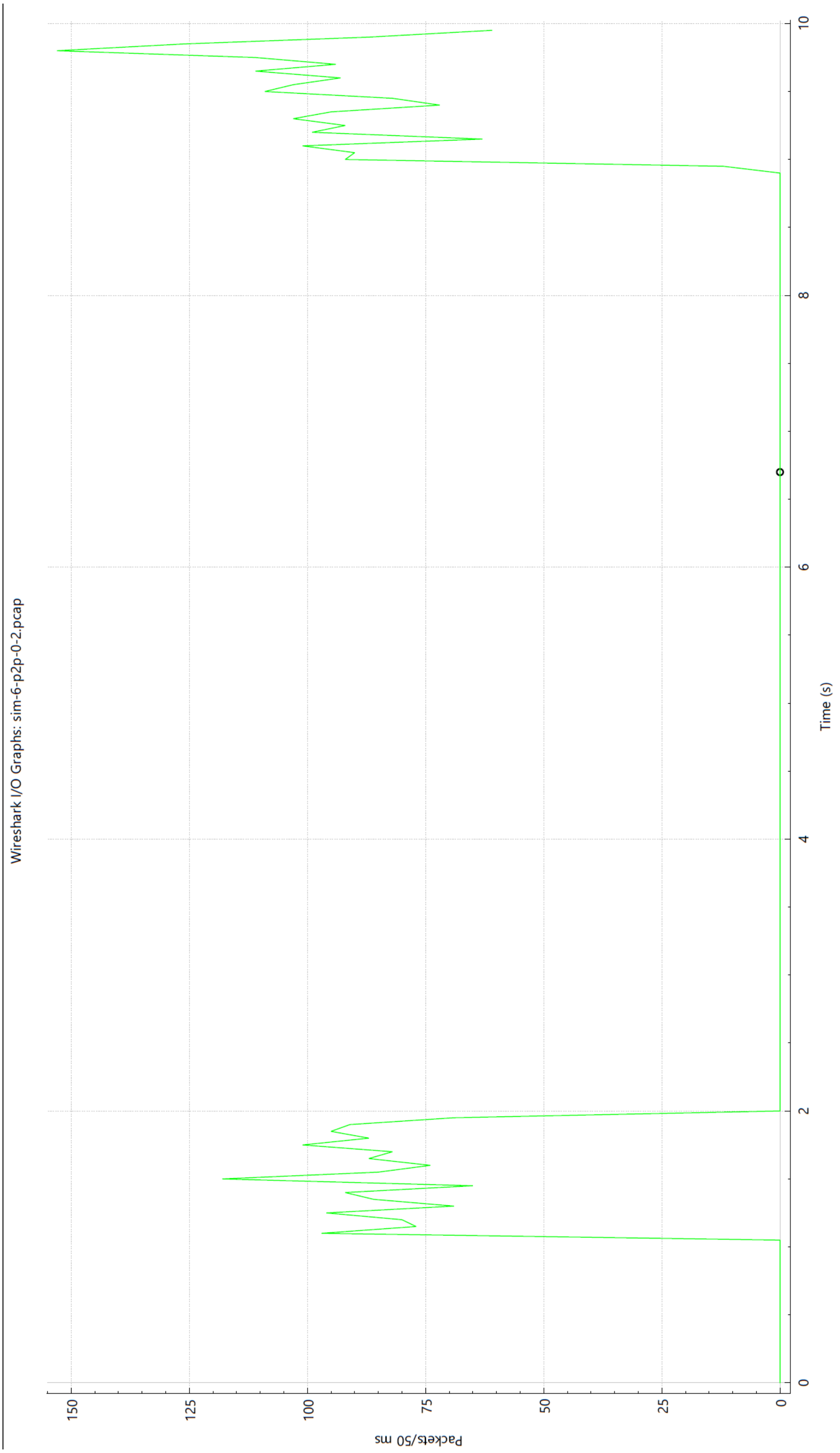


Wireshark I/O Graphs: sim-6-p2p-0-2.pcap
Time (s)
Packets/50 ms
0
2
4
6
8
10
0
100
200
300
400
500

TCP:

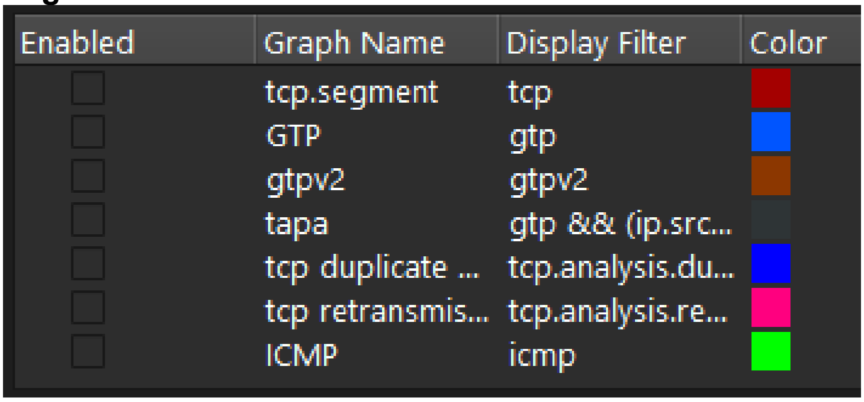


ICMP:



Wireshark I/O Graphs: sim-6-p2p-0-2.pcap
Time (s)
Packets/50 ms
0
2
4
6
8
10
0
25
50
75
100
125
150

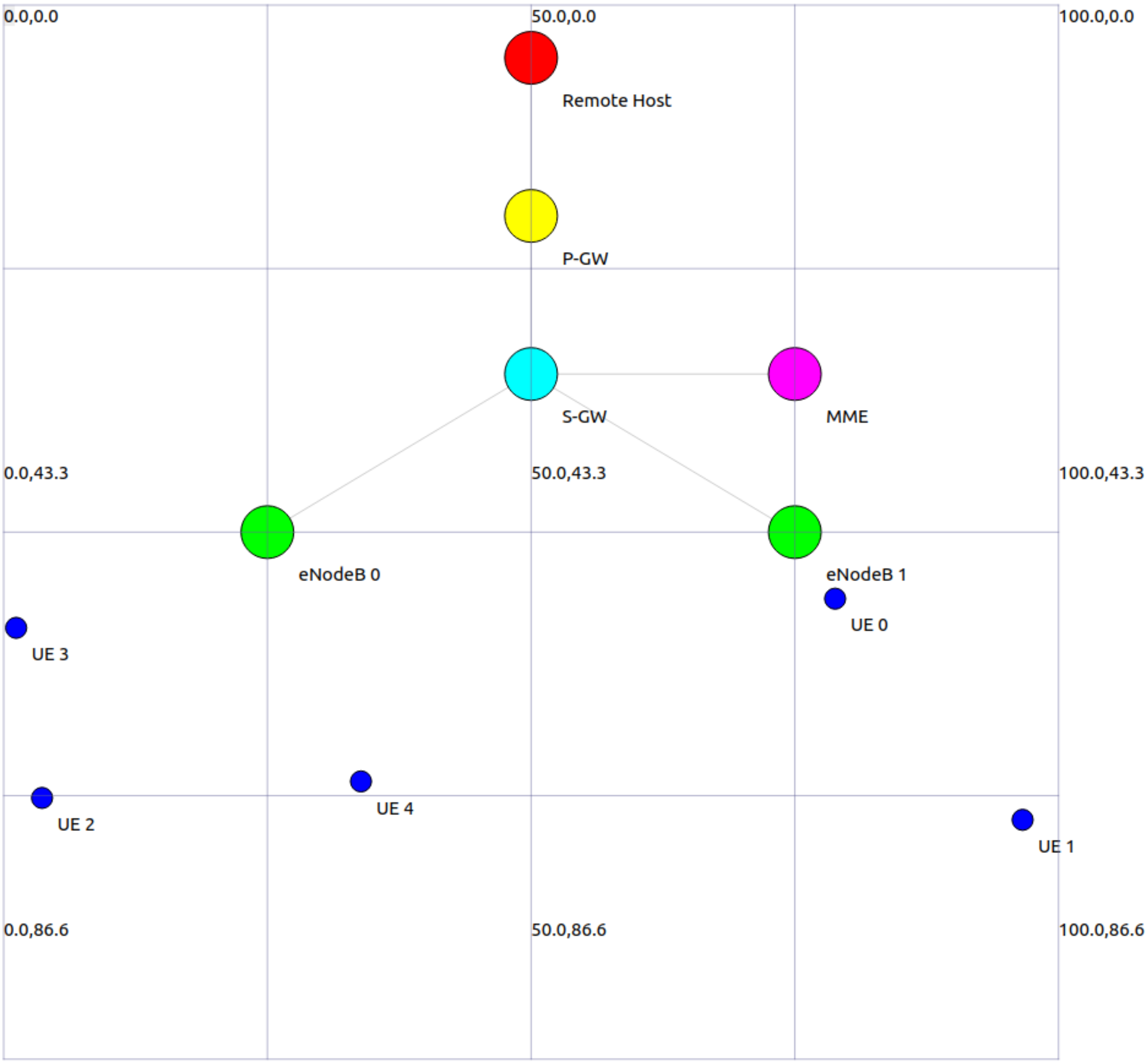
Legend:



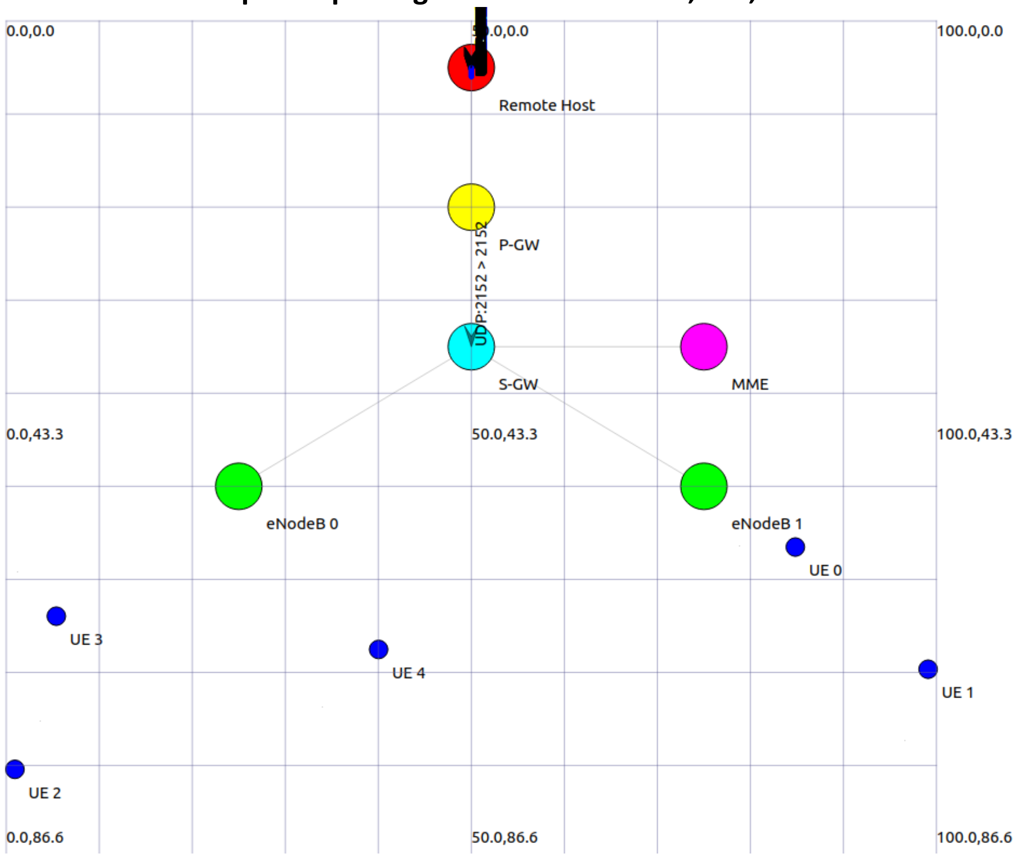
Enabled	Graph Name	Display Filter	Color
	tcp.segment	tcp	
	GTP	gtp	
	gtpv2	gtpv2	
	tapa	gtp && (ip.src...	
	tcp duplicate ...	tcp.analysis.du...	
	tcp retransmis...	tcp.analysis.re...	
	ICMP	icmp	

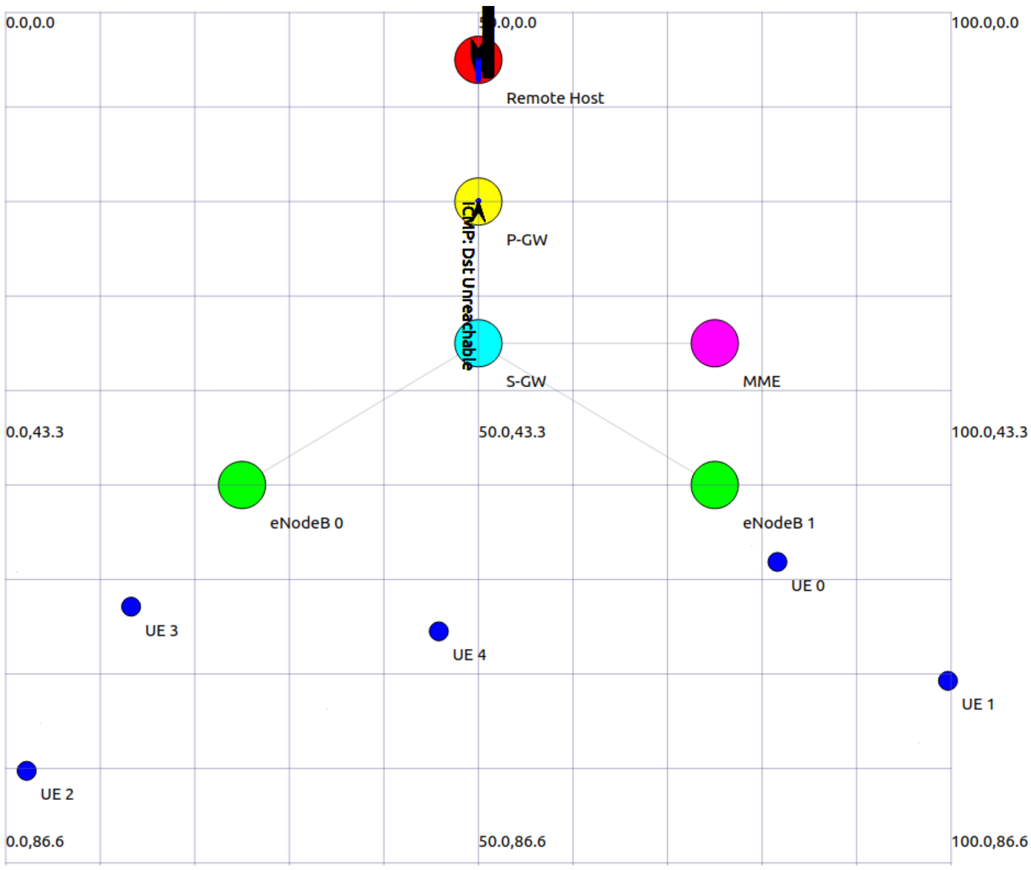
Simulation NetAnim:

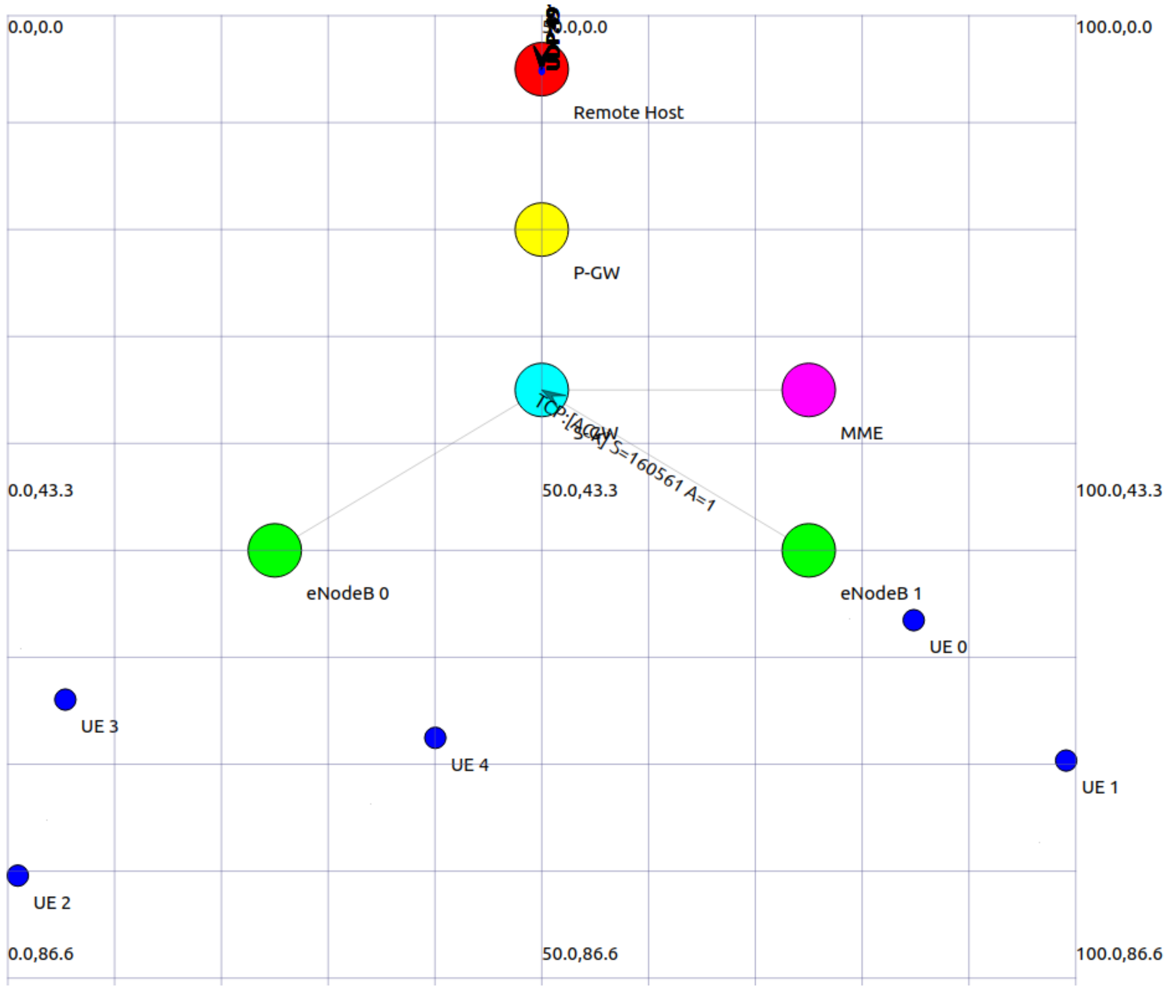
The displayed animation represents the LTE network topology, including its primary nodes and connections. This simulation provides a visual depiction of data flow and interaction between various elements of the LTE infrastructure. In this simulation, we can observe the movement of UEs.



Here are some examples capturing transmissions: UDP, TCP, ICMP:



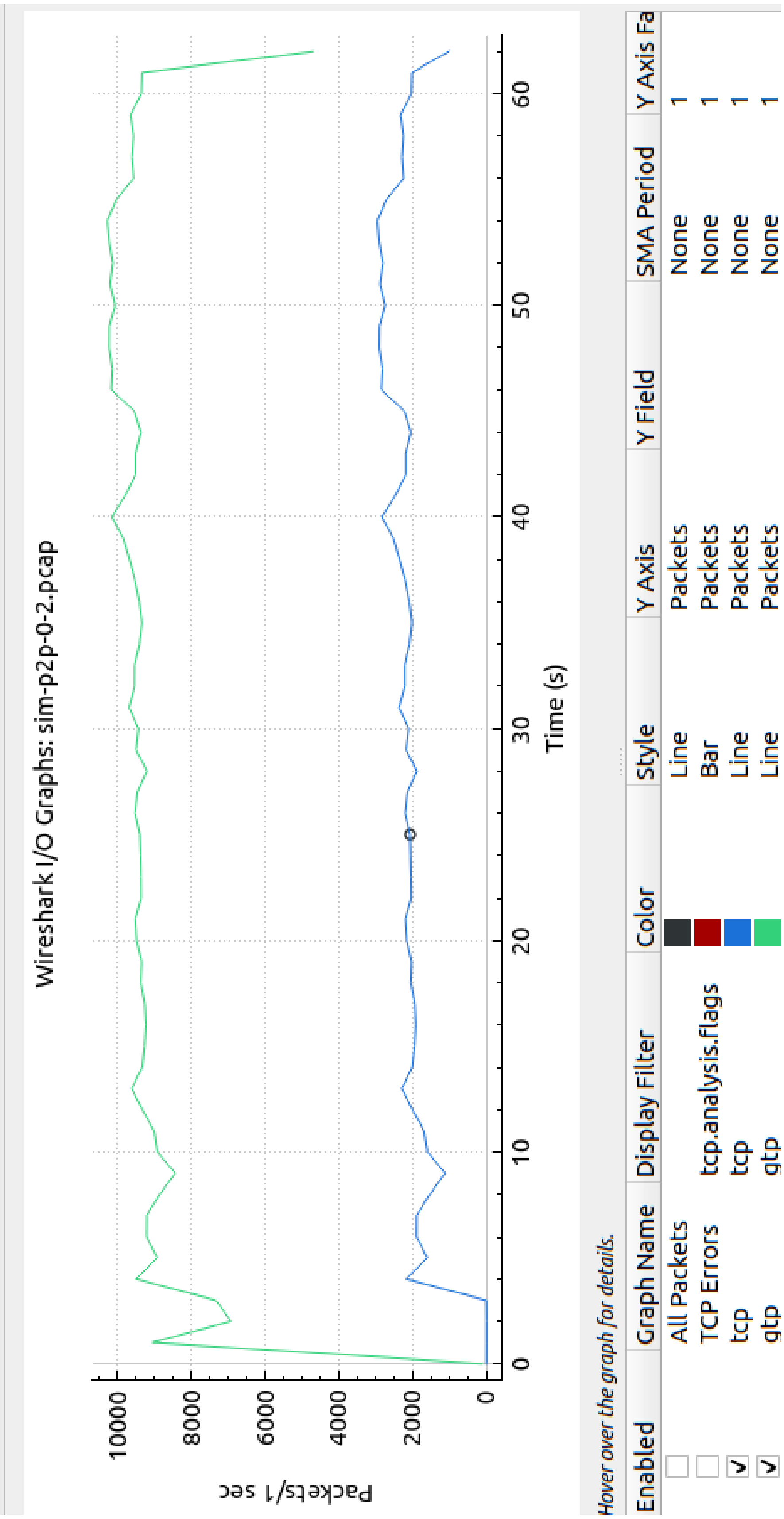




Stability Test:
Simulation time : 100 s

Scenario:	Stability test
Flow ID:	6
Src address:	7.0.0.3
Dst address:	7.0.0.2
Src port:	49153
Dst port:	4000
Tx Packets/Bytes:	1967/1142256
Rx Packets/Bytes:	1874/1088344
Throughput: [kb/s]	858.077
Delay sum:	39258 ms
Mean delay:	20.9488 ms
Jitter sum:	2884 ms
Mean jitter:	1,53997 ms
Lost Packets:	93
Packet loss: [%]	4,72801

The results are similar to the previous scenarios. There is no indication of increased instability, disconnection, or significant packet loss.



4. Any issues encountered during the simulation and how they were resolved:

a) Packet Loss Observed in UDP Traffic

- **Issue:** High levels of packet loss were observed during the transmission of UDP traffic, especially in scenarios with lower backbone bandwidth or higher latency.

- **Resolution:** The application layer can be adjusted to include buffering mechanisms, ensuring smooth playback for simulated video streams. Network configurations, such as increasing queue size and adjusting traffic generation rates, optimizing to minimize packet drops.

b) TCP Retransmissions

- **Issue:** A significant number of TCP retransmissions occurred in certain scenarios, particularly those involving congested links or high delay.

- **Resolution:** TCP window size and timeout parameters can be fine-tuned to adapt to network conditions. The simulation time can be extended slightly to allow for complete data transfer without excessive packet retransmissions.

c) ICMP "Destination Unreachable" Errors

- **Issue:** ICMP packets indicating "Destination unreachable (Port unreachable)" were frequently generated during certain flows, signaling potential routing or configuration issues.

- **Resolution:** Network topology settings should be reviewed, and routing tables corrected to ensure proper forwarding of packets between nodes. GTP encapsulation can be re-validated to confirm accurate tunneling of user-plane traffic.

d) GTP Session Initialization Delays

- **Issue:** Delays in establishing GTP sessions between core network nodes (e.g., S-GW and P-GW) led to initial packet drops.

- **Resolution:** The timing of control-plane messages, such as Create Session Request and Create Session Response, can be adjusted to align with the data-plane initialization. Logging and debugging tools can be used to verify that session establishment occurred as expected.

e) Visualization Performance in NetAnim

- **Issue:** NetAnim experienced performance lags when visualizing large-scale topologies or high traffic scenarios.

- **Resolution:** The simulation can be segmented into smaller time windows to capture specific behaviors.

5. Recommendations for improving network performance (if applicable):

Based on the observations and analysis conducted during the simulation, the following recommendations can be made to enhance the performance of the simulated LTE network:

a) Implement QoS Mechanisms: Certain traffic types, such as video streaming, suffered from inconsistent throughput and packet loss. Introduce Quality of Service (QoS) policies to prioritize latency-sensitive traffic like video and VoIP. Use DiffServ (Differentiated Services) to classify and manage traffic, ensuring critical applications receive higher priority and optimal performance.

b) Optimize User Equipment (UE) Data Rates: Inefficiencies and dropped packets were observed in scenarios where UE data rates mismatched the network's capacity or application requirements. Configure UEs to operate at data rates aligned with the network's capacity. Implement adaptive bitrate streaming for video applications to dynamically adjust to available bandwidth, ensuring consistent quality without overloading the network. Provide additional configuration options for UEs, such as detailed application-level control or dynamic adaptation of mobility patterns.

c) Improve GTP and Control-Plane Efficiency: Delays in GTP session establishment negatively impacted initial data transfers. Streamline GTPv2 signaling procedures to minimize overhead and ensure faster session establishment. Introduce caching or pre-fetching mechanisms to mitigate delays and provide smoother transitions during session setups. Implement enhanced monitoring of GTP control-plane and user-plane properties, such as tunnel reliability and latency, to preemptively address performance issues.

d) Scale Mobility Management: Performance variability was observed during UE movements, especially during handovers. Optimize handover mechanisms to minimize disruptions by reducing signaling delays and improving resource allocation during transitions. Employ predictive mobility models to anticipate UE movements, proactively allocate resources, and reduce handover latency. Provide configuration options for mobility management parameters, enabling fine-tuned adjustments to align with specific simulation or real-world requirements.

e) Increase Network Resilience: Packet loss and ICMP errors were prevalent in congested or misconfigured scenarios. Introduce error-correction mechanisms at the application or transport layer to recover lost packets effectively. Regularly monitor and update routing tables to ensure accurate and efficient packet forwarding, minimizing delivery errors. Add monitoring tools to track specific transmission properties, such as jitter, delay variations, and throughput, for better real-time diagnostics and performance optimization.