LTE Network Simulation in NS-3

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Abstract

This project explores the simulation of an LTE network using the Network Simulator 3 (NS-3) framework to evaluate the impact of various network parameters on performance metrics such as throughput, latency, packet loss, and jitter. Key aspects of the project include analyzing mobility models, MAC schedulers, network area sizes, path loss parameters, and VoIP codec configurations. By conducting a series of targeted simulations, the project identifies how these parameters influence network behavior under different conditions. The findings provide insights into optimizing LTE network performance, highlighting trade-offs between resource efficiency, scalability, and communication quality.

1. Introduction

Introduction to LTE Networks

Long-Term Evolution (LTE) is a global standard for wireless broadband communication, providing high-speed data transmission and enhanced network capacity. LTE networks are integral to modern communication, supporting diverse applications such as Voice over IP (VoIP), video streaming, and real-time data services.

Project Objectives and Scope

The objective of this project is to simulate and analyze an LTE network using **NS-3 (Network Simulator 3)**. The simulations focus on exploring various configurations and parameters to understand their influence on key performance metrics.

The scope of this study includes:

- **Network Topology**:
    - Configuring scenarios with multiple eNodeBs and varying numbers of User Equipment (UE).
    - Experimenting with diverse UE densities to evaluate network scalability and resource allocation.
- **Mobility Models**:
    - Simulating both dynamic and stationary UE behaviors using models like RandomWaypoint and Constant Mobility.
- **Schedulers**:
    - Comparing the performance of multiple MAC schedulers, including Round Robin, Proportional Fair, and Time Division Fairness, under varying traffic loads.
- **Area Sizes and Path Loss**:
    - Testing different simulation area sizes and path loss exponent parameters to study signal attenuation and network scalability in suburban and dense environments.
- **VoIP Traffic Simulation**:
    - Generating VoIP traffic using OnOff applications and comparing the performance of various codecs, such as G.711, G.722.2, G.723.1, and G.729.

Co2. Methodology

2.1. Simulation Environment

All simulations were executed using **Network Simulator 3 (NS-3)** version **3.39**. Key NS-3 modules used were:

- **LTE Module**: Facilitates LTE-specific functionalities such as eNodeB and UE device modeling.
- **Mobility Module**: Simulates diverse mobility patterns of UEs.
- **Internet Module**: Implements IP addressing, routing, and Internet connectivity.
- **Applications Module**: Generates and manages VoIP traffic through applications like OnOff.
- **Flow Monitor Module**: Collects detailed flow-level statistics, including throughput, latency, jitter, and packet loss.
- **Animation Interface**: Visualizes network dynamics using NetAnim.

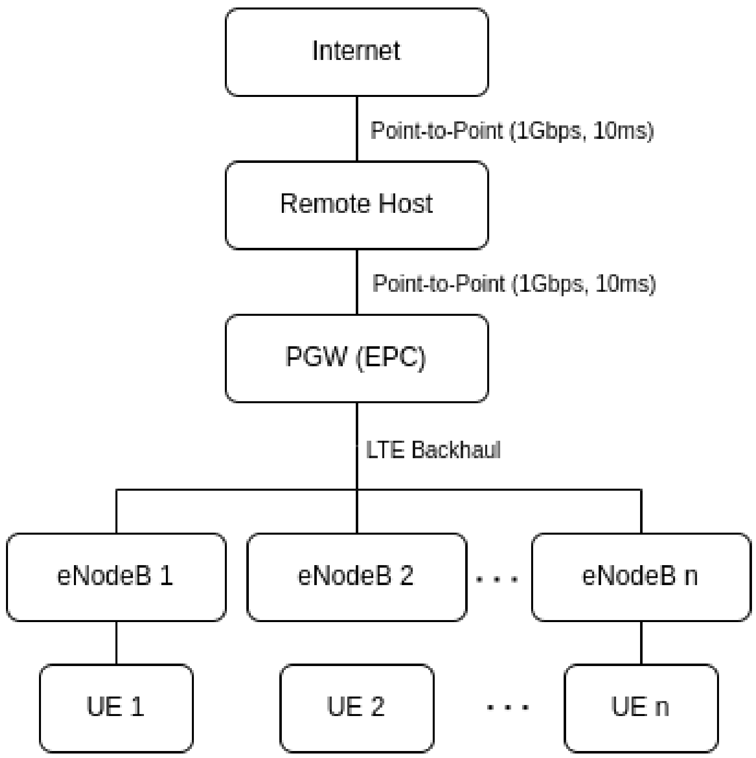


Diagram illustrating an LTE network topology, showcasing the connectivity from User Equipment (UE) to eNodeBs, through the Packet Gateway (PGW) and LTE backhaul, to a Remote Host via Point-to-Point link.

2.2. Mobility Models

Mobility significantly influences network performance by affecting factors such as handover frequency, latency, and packet loss. Various mobility models were employed to simulate different UE movement patterns:

- **RandomWaypointMobilityModel**:
    - **Description**: Simulates random movement patterns, similar to vehicle movement in suburban areas.
    - **Parameters**:
        - **Speed**: Random between **10–30 m/s**.
        - **Pause Time**: Fixed at **2 seconds** between movements.
    - **Usage**: Applied in multiple simulations to represent dynamic network topologies.
- **Constant Position Mobility Models**:
    - UEs remain stationary within specified distance constraints from the nearest eNodeB.

2.3. Path Loss Models

Accurate modeling of signal attenuation is crucial for realistic simulations. The **Three Log Distance Propagation Loss Model** was employed across all simulations to represent suburban environment characteristics effectively.

- **Parameters Configured**:
    - **Distance0**: **50.0 meters** – The first distance threshold for path loss calculation.
    - **Distance1**: **100.0 meters** – The second distance threshold.
    - **Exponent0**: **1.7** – Path loss exponent before Distance0.
    - **Exponent1**: **2.5** – Path loss exponent between Distance0 and Distance1.
    - **Exponent2**: **3.2** – Path loss exponent beyond Distance1.

2.4. Scheduler Configurations

Three different MAC schedulers were evaluated to determine their efficacy in handling VoIP traffic under varying network loads:

- **Round Robin (RrFfMacScheduler)**:
    - **Description**: Allocates resources to UEs in a fixed cyclic order, ensuring fair distribution.
- **Proportional Fair (PfFfMacScheduler)**:
    - **Description**: Balances fairness and throughput by allocating resources based on both UE demand and channel conditions.
- **Time Division Fairness (TdBetFfMacScheduler)**:
    - **Description**: Prioritizes UEs based on their time division fairness, aiming to optimize overall network throughput while maintaining fairness.

2.5. Traffic Generation

Voice over IP (VoIP) traffic was simulated to replicate voice communication scenarios.

- **Application Used**:
  - **OnOffApplication**: Configured to generate UDP packets that mimic VoIP traffic patterns.

2.6. Simulation Scenarios

In this project there were several simulation scenarios tested. Each scenario targeted specific aspects of the simulation code setup.

2.6.1. UE Placement

To assess the impact of UE placement relative to eNodeBs, UEs were positioned at varying distances:

- **Random**
- **Within Distance0**: UEs were placed within **50 meters** of the nearest eNodeB.
- **Within Distance1**: UEs were placed within **100 meters** of the nearest eNodeB.
- **Beyond Distance1**: UEs were positioned beyond **100 meters** from the nearest eNodeB.

2.6.2. Scheduler Comparison

Three different MAC schedulers were tested to evaluate their efficiency in resource allocation and performance:

- **Round Robin (RrFfMacScheduler)**
- **Proportional Fair (PfFfMacScheduler)**
- **Time Division Fairness (TdBetFfMacScheduler)**

2.6.3. Scheduler Comparison with Maxed-Out Bandwidth

To stress-test the schedulers, simulations were conducted with:

- **Maximum UE Count**: **75 UEs**
- **Minimal Bandwidth Allocation**: **1.4 MHz** (6 Downlink/ Uplink Resource Blocks)

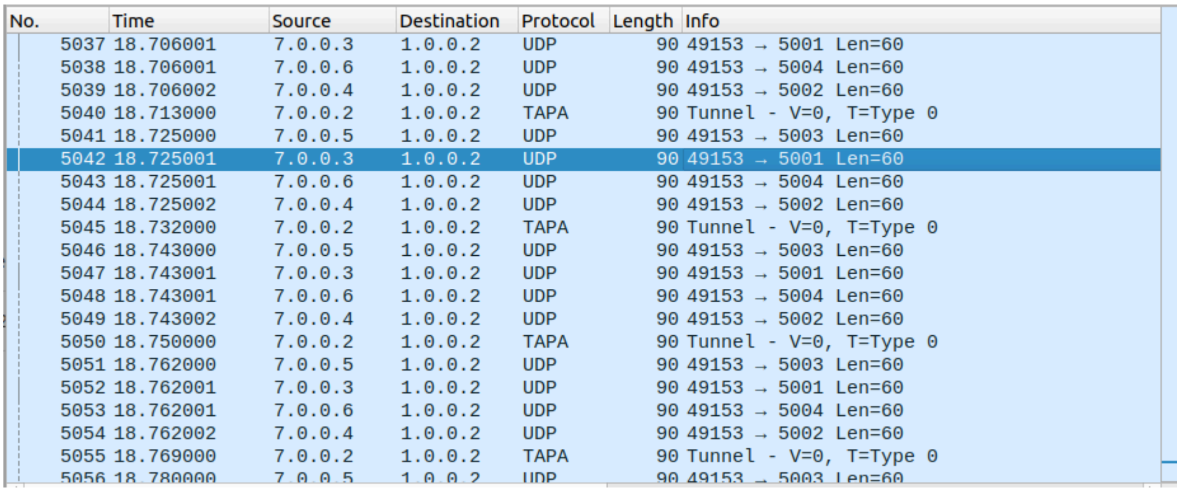
2.6.4. VoIP Codec Comparison

Various VoIP codecs were compared to analyze their impact on network performance:

- **Codecs Tested**: G.711, G.722.2, G.723.1, and G.729

Different codecs were tested by applying these parameters to **OnOffApplication:**

Codec Name	Bit Rate	Packet Size	Frame Size
G.711	64 kbps	80 bytes	10 ms
G.722.2	25.84 kbps	60 bytes	20 ms
G.723.1	6.3 kbps	24 bytes	30 ms
G.729	8 kbps	10 bytes	10 ms



No.	Time	Source	Destination	Protocol	Length	Info
5037	18.706001	7.0.0.3	1.0.0.2	UDP	90	49153 → 5001 Len=60
5038	18.706001	7.0.0.6	1.0.0.2	UDP	90	49153 → 5004 Len=60
5039	18.706002	7.0.0.4	1.0.0.2	UDP	90	49153 → 5002 Len=60
5040	18.713000	7.0.0.2	1.0.0.2	TAPA	90	Tunnel - V=0, T=Type 0
5041	18.725000	7.0.0.5	1.0.0.2	UDP	90	49153 → 5003 Len=60
5042	18.725001	7.0.0.3	1.0.0.2	UDP	90	49153 → 5001 Len=60
5043	18.725001	7.0.0.6	1.0.0.2	UDP	90	49153 → 5004 Len=60
5044	18.725002	7.0.0.4	1.0.0.2	UDP	90	49153 → 5002 Len=60
5045	18.732000	7.0.0.2	1.0.0.2	TAPA	90	Tunnel - V=0, T=Type 0
5046	18.743000	7.0.0.5	1.0.0.2	UDP	90	49153 → 5003 Len=60
5047	18.743001	7.0.0.3	1.0.0.2	UDP	90	49153 → 5001 Len=60
5048	18.743001	7.0.0.6	1.0.0.2	UDP	90	49153 → 5004 Len=60
5049	18.743002	7.0.0.4	1.0.0.2	UDP	90	49153 → 5002 Len=60
5050	18.750000	7.0.0.2	1.0.0.2	TAPA	90	Tunnel - V=0, T=Type 0
5051	18.762000	7.0.0.5	1.0.0.2	UDP	90	49153 → 5003 Len=60
5052	18.762001	7.0.0.3	1.0.0.2	UDP	90	49153 → 5001 Len=60
5053	18.762001	7.0.0.6	1.0.0.2	UDP	90	49153 → 5004 Len=60
5054	18.762002	7.0.0.4	1.0.0.2	UDP	90	49153 → 5002 Len=60
5055	18.769000	7.0.0.2	1.0.0.2	TAPA	90	Tunnel - V=0, T=Type 0
5056	18.780000	7.0.0.5	1.0.0.2	UDP	90	49153 → 5003 Len=60

Wireshark screenshot of UDP traffic using G.722.2 VoIP codec.

The screenshot captures UDP traffic between the remote host (1.0.0.2) and multiple UEs (7.0.0.3, 7.0.0.4, 7.0.0.5, 7.0.0.6). Each UDP packet has a data length of 60 bytes, corresponding to the packet size defined by the G.722.2 VoIP codec used in the simulation. This traffic represents the VoIP data generated by the OnOffApplication on the UEs, transmitted towards the remote host through the LTE network.

2.6.5. Area Size and Path Loss Parameters Scenarios

This scenario explored the impact of larger simulation areas and varied path loss exponents:

- **Area Sizes**: Ranging from **500 m²** to **100000 m²**.
- **Path Loss Exponents**: Adjusted to simulate suburban and dense urban environments.

3. Simulation

3.1. Code structure

The simulation code is organized into modules, each responsible for specific aspects of the simulation process.

1. Configuration

Allows us to manage all simulation parameters from a single place in code, for example:

```
struct SimulationParameters
{
   // Network Configuration
   uint16_t numEnb = 2;     ///< Number of eNodeBs
   uint16_t numUe = 50;     ///< Number of UEs
   double simTime = 20.0;   ///< Simulation time in seconds
   double areaSize = 200.0; ///< Size of the simulation area (square in meters)

   // Path Loss Model Parameters
   double distance0 = 50.0;  ///< First distance threshold in meters
   double distance1 = 100.0; ///< Second distance threshold in meters
   double exponent0 = 1.7;   ///< Path loss exponent before distance0
   double exponent1 = 2.5;   ///< Path loss exponent between distance0 and distance1
   double exponent2 = 3.2;   ///< Path loss exponent beyond distance1

   static constexpr double HANDOVER_HYSTERESIS = 3.0;      ///< Handover hysteresis in
dB
   static constexpr double HANDOVER_TimeToTrigger = 256.0; ///< Handover Time-To-Trigger
in ms
```

- **distance0** and **distance1**: Define distance thresholds used by the **ThreeLogDistancePropagationLossModel**. These thresholds categorize the simulation area into near, mid, and far zones relative to the eNodeBs.
- **exponent0**, **exponent1**, **exponent2**: Control the signal attenuation rates in each zone.

```
   // LTE Bandwidth Configuration
   uint16_t lteBandwidth = 1; ///< LTE Bandwidth in MHz
   /**
    * @brief LTE Bandwidth options (MHz) mapped to RBs.
    *
    * | Bandwidth (MHz) | Downlink RBs | Uplink RBs |
    * |-----------------|--------------|------------|
    * | 1.4   // 1      | 6            | 6          |
    * | 3               | 15           | 15         |
    * | 5               | 25           | 25         |
    * | 10              | 50           | 50         |
    * | 15              | 75           | 75         |
    * | 20              | 100          | 100        |
    */
   std::map<uint16_t, std::pair<uint16_t, uint16_t>> lteBandwidthMap;
```

- **lteBandwidthMap**: Maps each bandwidth value to the corresponding number of resource blocks (RBs) for uplink and downlink.

```
// Initialize VoIP codec (default: G.711)
        codec.name = "G.711";
        codec.bitrate = 64.0;  // kbps
        codec.packetSize = 80; // bytes

        // // G.722.2
        // codec.name = "G.722.2";
        // codec.bitrate = 25.84;
        // codec.packetSize = 60;

        // // G.723.1
        // codec.name = "G.723.1";
        // codec.bitrate = 6.3;
        // codec.packetSize = 24;

        // // G.729
        // codec.name = "G.729";
        // codec.bitrate = 8.0;
        // codec.packetSize = 10;
    }

    // VoIP Codec Parameters
    struct VoipCodec
    {
        std::string name;    ///< Codec name
        double bitrate;      ///< Bitrate in kbps
        uint32_t packetSize; ///< Packet size in bytes
    } codec;
```

- **VoipCodec**: Allows for quick change of codec parameters that are then used and created as traffic by **OnOffApplication** on each UE.

2. Node Creation Module
    - **Purpose:** Establishes eNodeBs (base stations), UEs (User Equipments), and the remote host (server).
    - **Components:**
        - **Node Containers:** Utilize NS-3's `NodeContainer` to manage groups of nodes efficiently.
        - **eNodeB and UE Initialization:** Creates specified numbers of eNodeBs and UEs based on the simulation parameters.

```
/**
* @brief Creates a remote host connected to the PGW via a Point-to-Point link.
* @param epcHelper EPC helper.
* @param remoteHostContainer Container holding the remote host node.
* @param areaSize Size of the simulation area.
* @return Ipv4Address of the remote host.
*/
Ipv4Address
CreateRemoteHost(Ptr<PointToPointEpcHelper> epcHelper,
                 NodeContainer& remoteHostContainer,
                 double areaSize)
{
   Ptr<Node> pgw = epcHelper->GetPgwNode();
   PointToPointHelper p2p;
   p2p.SetDeviceAttribute("DataRate", StringValue("1Gbps"));
   p2p.SetChannelAttribute("Delay", StringValue("10ms"));

   NetDeviceContainer devices = p2p.Install(pgw, remoteHostContainer.Get(0));
   Ipv4AddressHelper ipv4;
   ipv4.SetBase("1.0.0.0", "255.255.255.0");
   Ipv4InterfaceContainer interfaces = ipv4.Assign(devices);

   // Enable PCAP tracing
   p2p.EnablePcap("pgw-p2p", devices.Get(0), true);
   p2p.EnablePcap("remote-host-p2p", devices.Get(1), true);

   return interfaces.GetAddress(1); // Remote Host IP
}
```

3. Mobility Configuration Module
    - **Purpose:** Assigns mobility models to network nodes, determining how UEs move within the simulation environment.
    - **Components:**
        - **`ConfigureEnbMobility()` Function:** Positions two or four eNodeBs using a `ConstantPositionMobilityModel.`
        - **`ConfigureUeMobility()` Function:** Applies selected mobility models to UEs (random waypoint movement or constant positioning).

```
void
ConfigureEnbMobility(NodeContainer& enbNodes, double areaSize)
{
    MobilityHelper enbMobility;
    Ptr<ListPositionAllocator> posAlloc = CreateObject<ListPositionAllocator>();

    if (enbNodes.GetN() == 4)
    {
        // Four eNodeBs: Default positioning (corners)
        posAlloc->Add(Vector(areaSize / 4, areaSize / 4, 30.0));         // Bottom-left
        posAlloc->Add(Vector(areaSize / 4, 3 * areaSize / 4, 30.0));     // Top-left
        posAlloc->Add(Vector(3 * areaSize / 4, areaSize / 4, 30.0));     // Bottom-right
        posAlloc->Add(Vector(3 * areaSize / 4, 3 * areaSize / 4, 30.0)); // Top-right
    }
    else if (enbNodes.GetN() == 2)
    {
        // Two eNodeBs: Centered along the Y-axis
        posAlloc->Add(Vector(areaSize / 4, areaSize / 2, 30.0));     // Center-left
        posAlloc->Add(Vector(3 * areaSize / 4, areaSize / 2, 30.0)); // Center-right
    }
    else
```

4. Application Installation Module
    - Deploys VoIP traffic applications on UEs and sets up corresponding packet sinks on the remote host to facilitate communication.
    - **Components:**
        - **`InstallVoipApplications()`:** Configures the OnOff applications to simulate VoIP traffic, setting bitrate and packet size parameters based on the chosen codec.

```
// Configure OnOff application to simulate VoIP traffic
OnOffHelper onOff("ns3::UdpSocketFactory", InetSocketAddress(remoteAddr, port));
onOff.SetAttribute("DataRate", DataRateValue(DataRate(params.codec.bitrate * 1000)));
onOff.SetAttribute("PacketSize", UintegerValue(params.codec.packetSize));
onOff.SetAttribute("OnTime", StringValue("ns3::ConstantRandomVariable[Constant=1]"));
onOff.SetAttribute("OffTime", StringValue("ns3::ConstantRandomVariable[Constant=0]"));

// Install OnOff application on UE
ApplicationContainer apps = onOff.Install(ueNodes.Get(i));
apps.Start(Seconds(1.0));
apps.Stop(Seconds(simTime));
```

5. Tracing and Logging Module
   - Tracing of network events and logging

```
/**
 * @brief Configures the logging levels for various components.
 */
void
ConfigureLogging()
{
    LogComponentEnable("VoipLteSimulation", LOG_LEVEL_INFO); // Simulation defined logs
    LogComponentEnable("LteEnbRrc", LOG_LEVEL_INFO);
    LogComponentEnable("LteUeRrc", LOG_LEVEL_INFO);
    // Uncomment to enable more detailed logging
    // LogComponentEnable("OnOffApplication", LOG_LEVEL_INFO);
    // LogComponentEnable("PacketSink", LOG_LEVEL_INFO);
}
```

6. NetAnim Module
   - Provides visual representations of the simulation through NetAnim. In the animation we can see UE nodes moving randomly and the eNBs being stationary.

```
// Initialize NetAnim
AnimationInterface* anim = nullptr;
if (params.enableNetAnim)
{
   anim = new AnimationInterface("animation.xml");
   anim->SetMaxPktsPerTraceFile(5000000);

   // Configure eNodeBs in NetAnim
   for (uint32_t i = 0; i < enbNodes.GetN(); ++i)
   {
       Ptr<Node> enbNode = enbNodes.Get(i);
       Vector pos = enbNode->GetObject<MobilityModel>()->GetPosition();
       anim->UpdateNodeDescription(enbNode, "eNodeB_" + std::to_string(i));
       anim->UpdateNodeColor(enbNode, 0, 0, 255); // Blue
       anim->SetConstantPosition(enbNode, pos.x, pos.y);
   }

   // Configure UEs in NetAnim
   for (uint32_t i = 0; i < ueNodes.GetN(); ++i)
   {
       Ptr<Node> ueNode = ueNodes.Get(i);
       Vector pos = ueNode->GetObject<MobilityModel>()->GetPosition();
       anim->UpdateNodeDescription(ueNode, "UE_" + std::to_string(i));
       anim->UpdateNodeColor(ueNode, 0, 255, 0); // Green
       anim->SetConstantPosition(ueNode, pos.x, pos.y);
   }
```

7. Data Analysis Module
    - **Purpose:** Processes and analyzes simulation data post-execution, generating summaries and visual plots to interpret performance metrics.
    - **Components:**
        - `AnalyzeData()` **Function:** Extracts and processes FlowMonitor data, generates Gnuplot scripts for visualization, and exports metrics to CSV files for further analysis.
        -

```cpp
/**
* @brief Analyzes the flow monitor data after simulation ends and generates reports.
* @param flowHelper FlowMonitorHelper instance.
* @param flowMonitor FlowMonitor instance.
* @param params Simulation parameters.
* @param remoteHostAddr IP address of the remote host.
* @param ueAddresses Vector of UE IP addresses.
*/
void
AnalyzeData(FlowMonitorHelper& flowHelper,
           Ptr<FlowMonitor> flowMonitor,
           const SimulationParameters& params,
           Ipv4Address remoteHostAddr,
           const std::vector<Ipv4Address>& ueAddresses)
{
```

4. Results

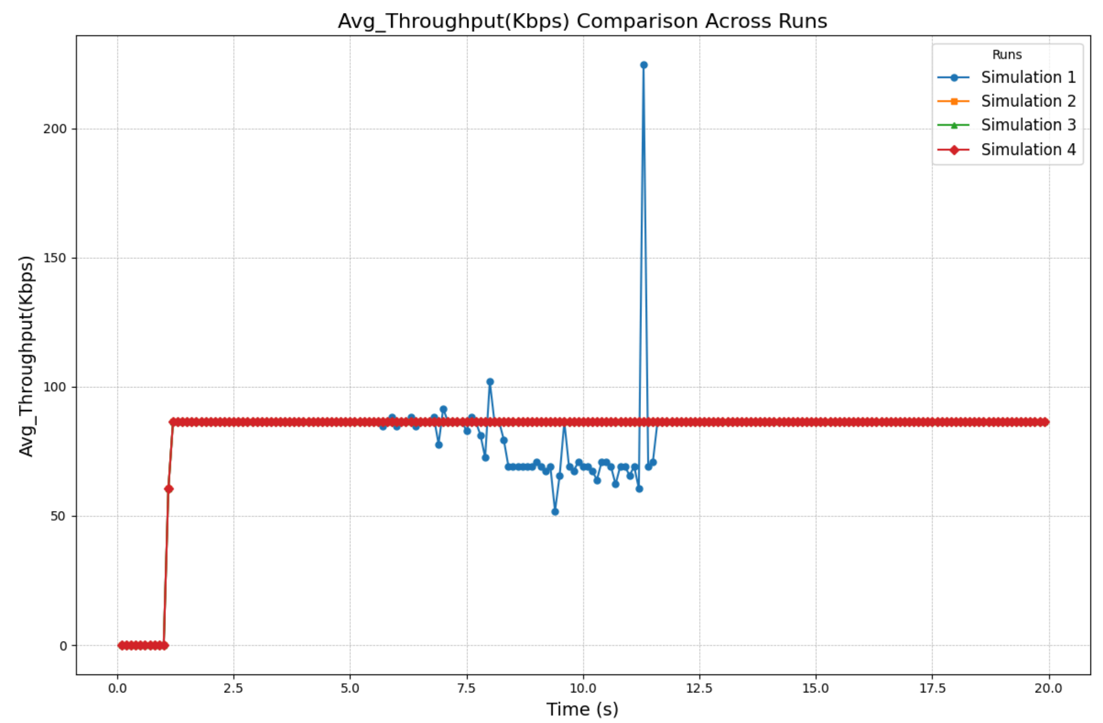
4.1. Parameter and Component Experiments

4.1.1. UE Placement in ThreeLogDistance Path Loss Model

This experiment analyzed the impact of UE placement relative to eNodeBs on network performance.

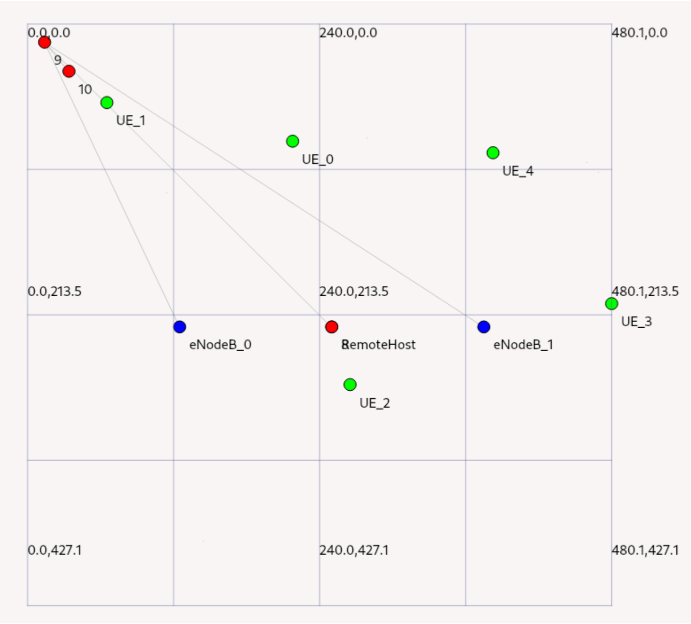
- **Simulation 1** uses a **RandomWaypointMobilityModel** and randomly places UE nodes which then move at random speed in random directions.
- **Simulations 2, 3, 4** place their UE nodes with **ConstantMobilityModel** at a range that fits inside the distance parameters in **ThreeLogDistancePropagationLossModel.**

Parameter	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Area size	500.0 m	500.0 m	500.0 m	500.0 m
# of eNodeBs	2	2	2	2
# of UEs	5	5	5	5
Remote Hosts	1	1	1	1
Scheduler	RrFfMacScheduler	RrFfMacScheduler	RrFfMacScheduler	RrFfMacScheduler
Hysteresis Handover	3 dB	3 dB	3 dB	3.0 dB
Hysteresis TTT	256 ms	256 ms	256 ms	120 ms
Path Loss Model	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance
Path Loss Parameters	Default	Default	Default	Default
- Distance0	50.0 m	50.0 m	50.0 m	50.0 m
- Distance1	100.0 m	100.0 m	100.0 m	100.0 m
- Exponent0	1.7	1.7	1.7	1.7
- Exponent1	2.5	2.5	2.5	2.5
- Exponent2	3.2	3.2	3.2	3.2
Buildings	No	No	No	No
VoIP Codec	G.711	G.711	G.711	G.711
Data Rate (kbps)	64	64	64	64
Packet Size (bytes)	80	80	80	80
Mobility Model	RandomWaypoint Mobility Model	Constant (<Distance0)	Constant (<Distance1)	Constant (>Distance1)



Average Throughput of Simulations 1-4.

As shown in the plot above, the UE nodes in **Simulation 1** move randomly, causing variations in the signal. In contrast, **Simulations 2, 3, 4** demonstrate consistent average throughput due to the static placement of UE nodes.



Screenshot of simulation area with eNB and UE nodes from Simulation 1.

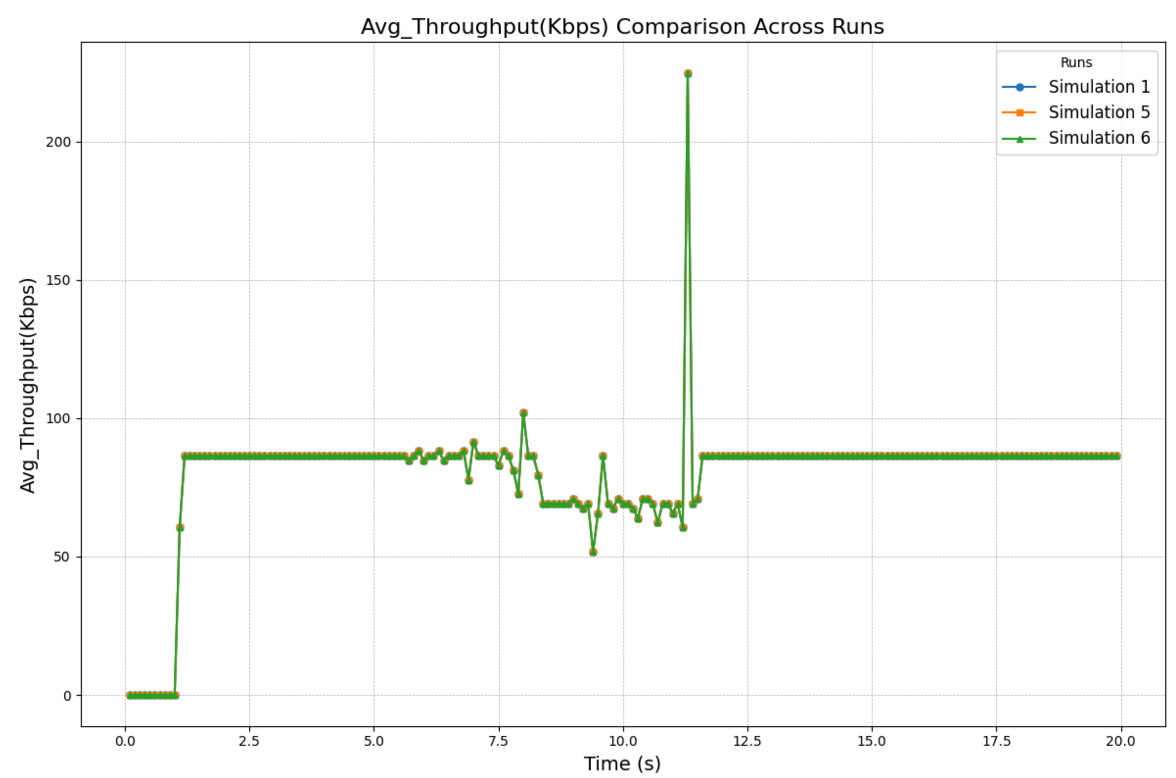
The placement of UE nodes within different ranges of the ThreeLogDistance model parameters had minimal impact, with the simulations exhibiting nearly identical behavior.

4.2. Scheduler Comparison

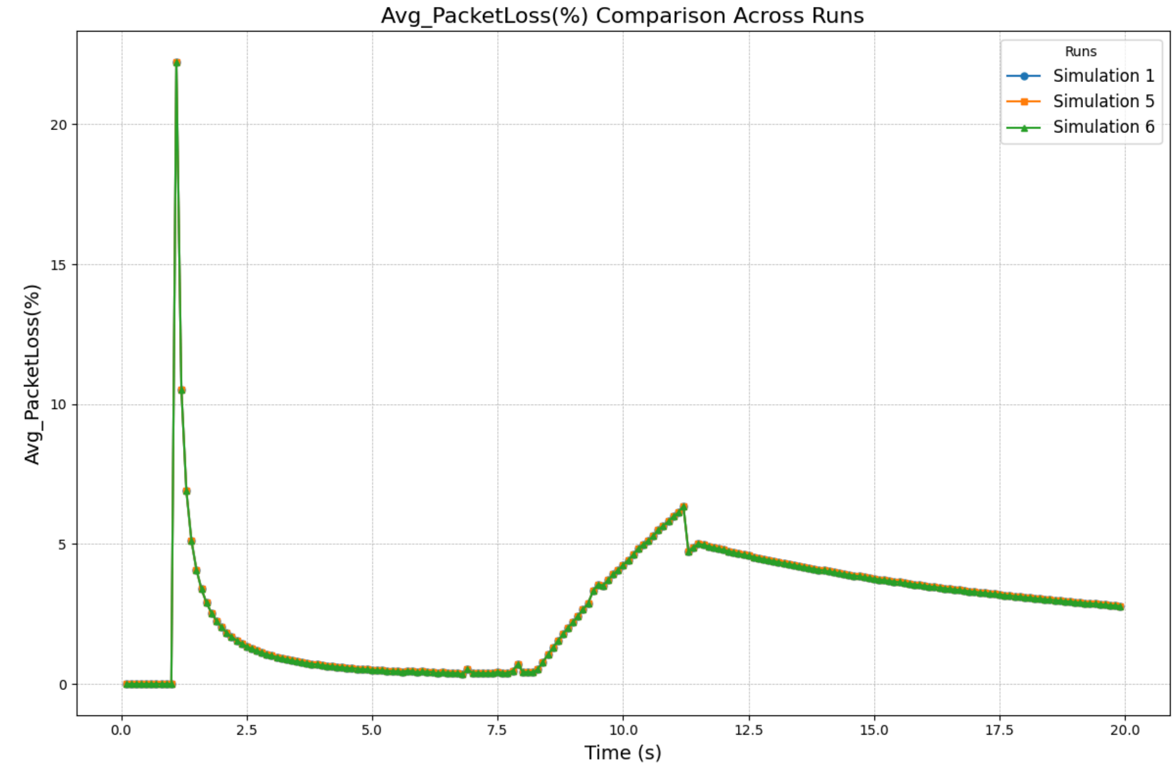
Three MAC schedulers were compared:

- Round Robin (RrFfMacScheduler)
- Proportional Fair (PfFfMacScheduler)
- Time Division Fairness (TdBetFfMacScheduler)

Parameter	Simulation 1	Simulation 5	Simulation 6
Area size	500.0 m	500.0 m	500.0 m
# of eNodeBs	2	2	2
# of UEs	5	5	5
Remote Hosts	1	1	1
Scheduler	RrFfMacScheduler	TdBetFfMacScheduler	PfFfMacScheduler



Identical average throughput of Simulations 1, 5, 6.



Identical average packet loss of Simulations 1, 5, 6.

In the graphs above we can see identical metrics for all three MAC schedulers across **Simulations 1, 5, 6**. Reasons for that might be the lack of difference in parameters across the simulations, identical traffic type (G.711 codec) and no need for scheduling since the number of UEs was too low (5).

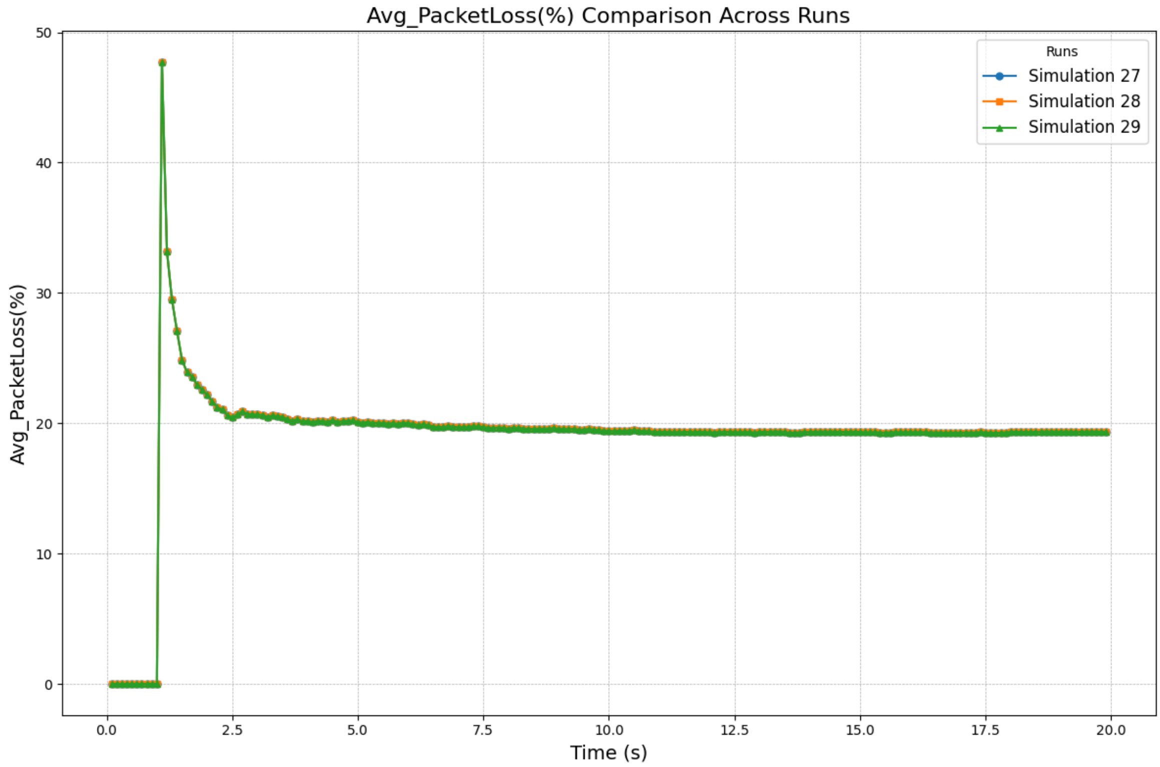
As a result, the scheduling mechanisms lead to negligible differences in their behavior.

4.2.1. Scheduler Comparison with Maxed-Out Bandwidth

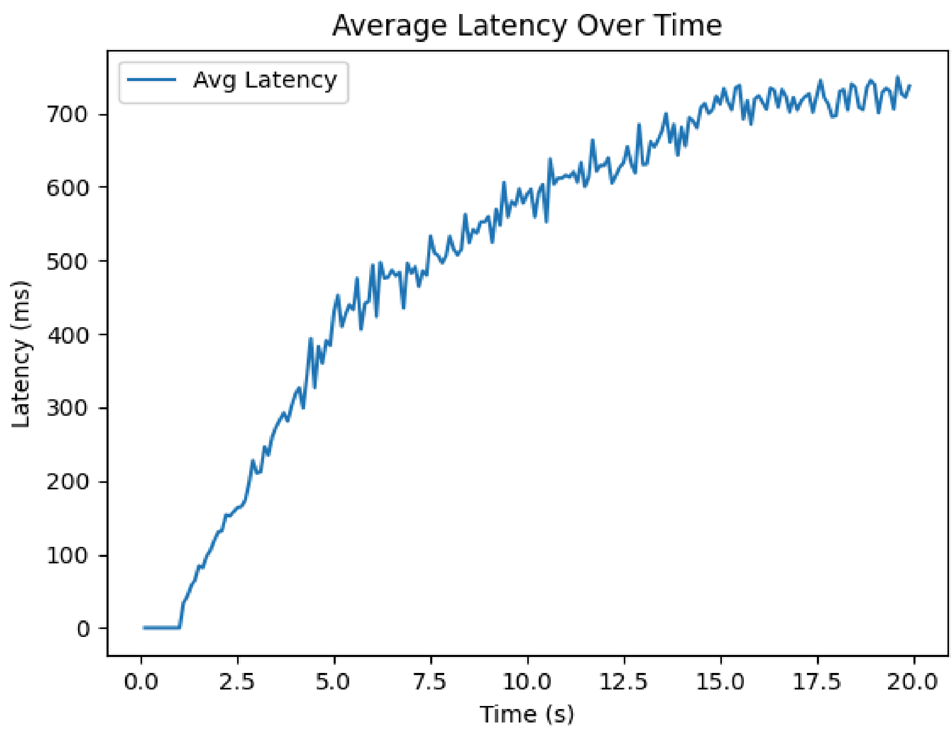
The schedulers were tested under extreme conditions:

- Raised UE count: 75 UEs
- Minimal bandwidth: 1.4 MHz
- UEs were placed stationary under Distance1 (within 100 meters of the eNodeB), minimizing signal propagation loss.

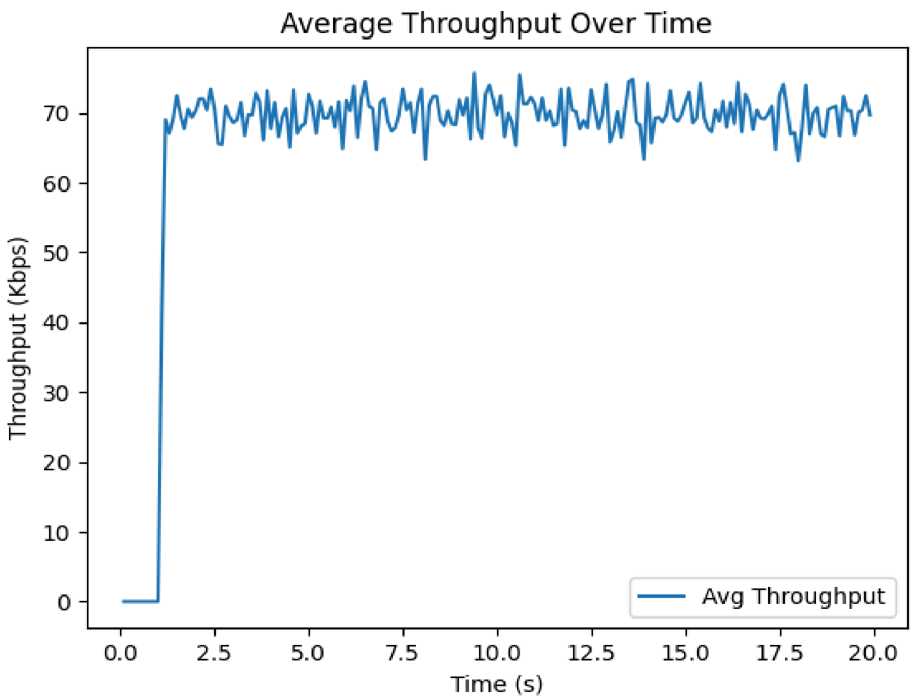
Parameter	Simulation 27	Simulation 28	Simulation 29
Area size	200 m	200 m	200 m
# of eNodeBs	2	2	2
# of UEs	75	75	75
Remote Hosts	1	1	1
Scheduler	RrFfMacScheduler	TdBetFfMacScheduler	PfFfMacScheduler
Hysteresis Handover	3 dB	3 dB	3 dB
Hysteresis TTT	120 ms	120 ms	120 ms
Path Loss Model	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance
Path Loss Parameters	Default	Default	Default
- Distance0	50.0 m	50.0 m	50.0 m
- Distance1	100.0 m	100.0 m	100.0 m
- Exponent0	1.7	1.7	1.7
- Exponent1	2.5	2.5	2.5
- Exponent2	3.2	3.2	3.2
Buildings	No	No	No
VoIP Codec	G.711	G.711	G.711
Data Rate (kbps)	64	64	64
Packet Size (bytes)	80	80	80
Mobility Model	Constant < Distance1	Constant < Distance1	Constant < Distance1
DL/UL Bandwidth (MHz)	1	1	1
DL Resource Blocks	6	6	6
UL Resource Blocks	6	6	6



Average packet loss of traffic in Simulations 27, 28, 29



Average latency of traffic in Simulation 29.

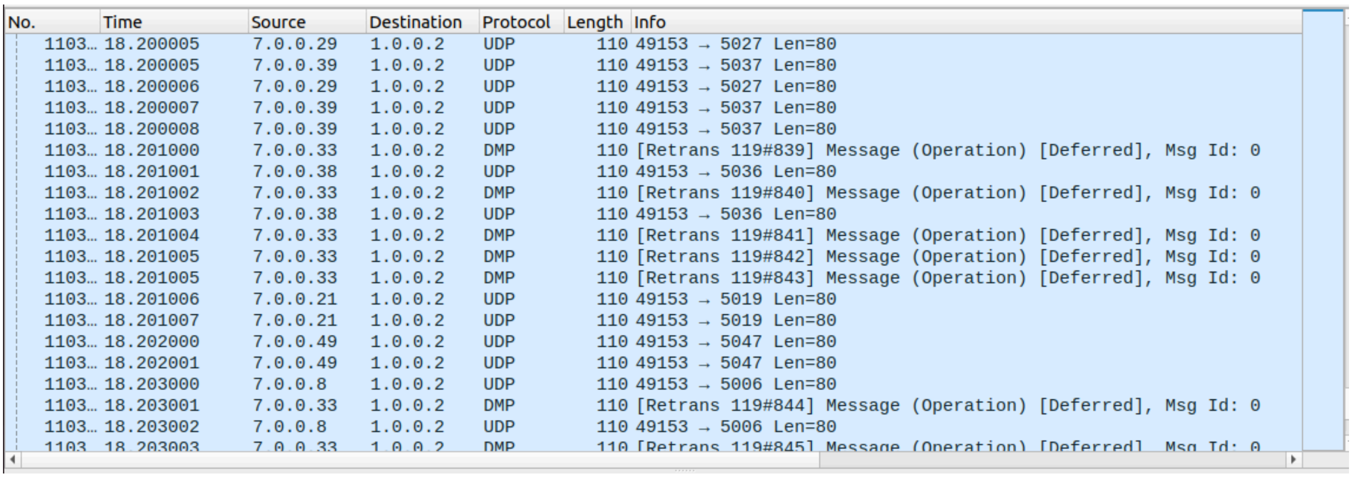


Average throughput of traffic in Simulation 29.

Despite the higher network demand and minimal bandwidth allocation, the metrics—throughput, latency, packet loss, and jitter—**show no variation between the schedulers**.

For one of these extreme conditions **Simulation 29**, in the graphs above, we can see the average latency getting steadying bigger throughout this simulation under extreme conditions. The reasons for this could be

- The network has reached its **maximum throughput capacity**
- As packets arrive faster than they can be transmitted, the **transmission queues grow over time**.



No.	Time	Source	Destination	Protocol	Length	Info
1103…	18.200005	7.0.0.29	1.0.0.2	UDP	110	49153 → 5027 Len=80
1103…	18.200005	7.0.0.39	1.0.0.2	UDP	110	49153 → 5037 Len=80
1103…	18.200006	7.0.0.29	1.0.0.2	UDP	110	49153 → 5027 Len=80
1103…	18.200007	7.0.0.39	1.0.0.2	UDP	110	49153 → 5037 Len=80
1103…	18.200008	7.0.0.39	1.0.0.2	UDP	110	49153 → 5037 Len=80
1103…	18.201000	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#839] Message (Operation) [Deferred], Msg Id: 0
1103…	18.201001	7.0.0.38	1.0.0.2	UDP	110	49153 → 5036 Len=80
1103…	18.201002	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#840] Message (Operation) [Deferred], Msg Id: 0
1103…	18.201003	7.0.0.38	1.0.0.2	UDP	110	49153 → 5036 Len=80
1103…	18.201004	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#841] Message (Operation) [Deferred], Msg Id: 0
1103…	18.201005	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#842] Message (Operation) [Deferred], Msg Id: 0
1103…	18.201005	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#843] Message (Operation) [Deferred], Msg Id: 0
1103…	18.201006	7.0.0.21	1.0.0.2	UDP	110	49153 → 5019 Len=80
1103…	18.201007	7.0.0.21	1.0.0.2	UDP	110	49153 → 5019 Len=80
1103…	18.202000	7.0.0.49	1.0.0.2	UDP	110	49153 → 5047 Len=80
1103…	18.202001	7.0.0.49	1.0.0.2	UDP	110	49153 → 5047 Len=80
1103…	18.203000	7.0.0.8	1.0.0.2	UDP	110	49153 → 5006 Len=80
1103…	18.203001	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#844] Message (Operation) [Deferred], Msg Id: 0
1103…	18.203002	7.0.0.8	1.0.0.2	UDP	110	49153 → 5006 Len=80
1103…	18.203003	7.0.0.33	1.0.0.2	DMP	110	[Retrans 119#845] Message (Operation) [Deferred], Msg Id: 0

The captured packets, such as the one in the screenshot (`7.0.0.33 → 1.0.0.2, DMP, [Retrans 119#842]`), demonstrate this behavior, highlighting how the network struggles to handle the load, resulting in deferred operations and repeated attempts to send the same data.

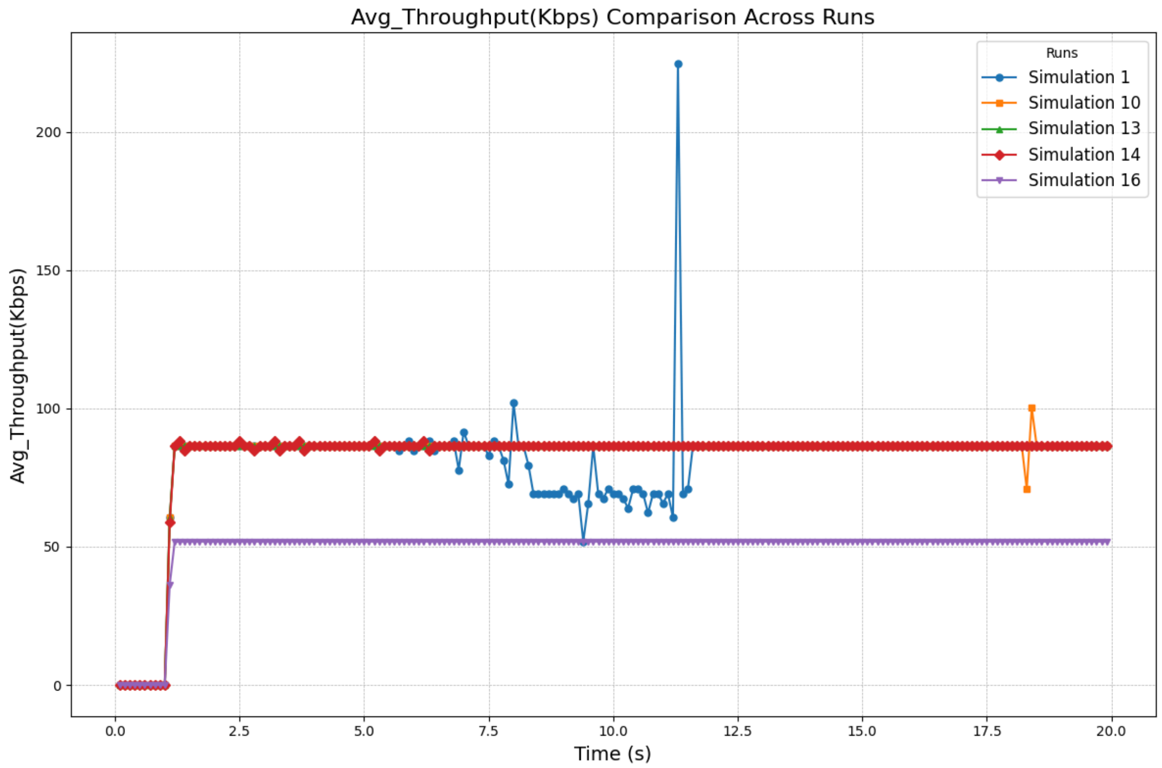
4.3. Area Size and Propagation Loss Parameter Experiments

Different area sizes and path loss exponent configurations were tested to understand their impact on network performance:

- Area sizes: 500 m² to 100000 m²
- Path loss exponents: Adjusted for suburban and dense urban environments

4.3.1 Area size simulations

Parameter	Simulation 1	Simulation 10	Simulation 13	Simulation 14	Simulation 16
Area size	500.0 m	2000 m	5000 m	10000 m	100000 m
# of eNodeBs	2	2	2	2	2
# of UEs	5	5	5	5	5
Remote Hosts	1	1	1	1	1
Scheduler	RrFfMac	RrFfMac	RrFfMac	RrFfMac	RrFfMac
Hysteresis Handover	3 dB	3 dB	3 dB	3 dB	3 dB
Hysteresis TTT	120 ms	120 ms	120 ms	120 ms	120 ms
Path Loss Model	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance
Path Loss Parameters	Default	Default	Default	Default	Default
- Distance0	50.0 m	50.0 m	50.0 m	50.0 m	50.0 m
- Distance1	100.0 m	100.0 m	100.0 m	100.0 m	100.0 m
- Exponent0	1.7	1.7	1.7	1.7	1.7
- Exponent1	2.5	2.5	2.5	2.5	2.5
- Exponent2	3.2	3.2	3.2	3.2	3.2
Buildings	No	No	No	No	No
VoIP Codec	G.711	G.711	G.711	G.711	G.711
Data Rate (kbps)	64	64	64	64	64
Packet Size (bytes)	80	80	80	80	80
Mobility Model	RandomWaypoint	RandomWaypoint	RandomWaypoint	RandomWaypoint	RandomWaypoint
UE Speed (m/s)	10–30	10–30	10–30	10–30	10–30
Pause Time (s)	2.0	2.0	2.0	2.0	2.0



Average Throughput of Simulations 1, 10, 13, 14, 16.

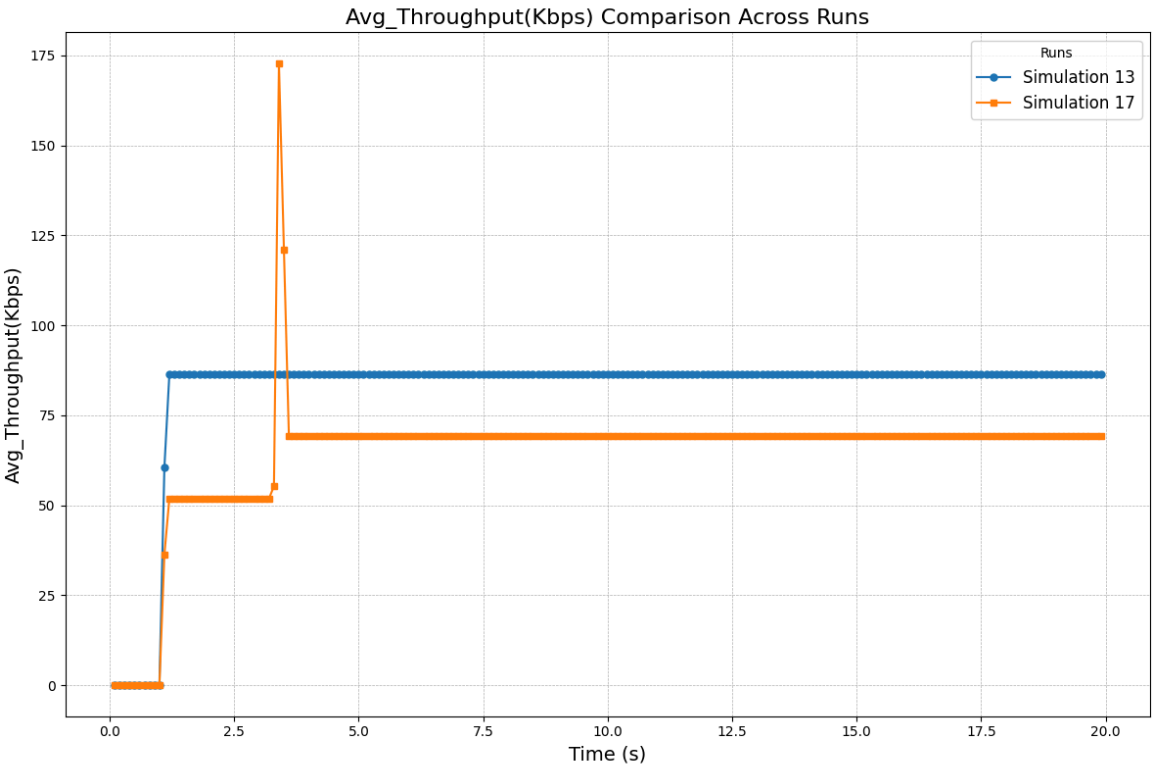
The average throughput across the simulations demonstrates a consistent performance up to **Simulation 14** but drops significantly in **Simulation 16** as the area size and the distances between UE and eNbs get bigger and multiple UE nodes are completely out of range.

4.3.2 Propagation loss parameters simulations

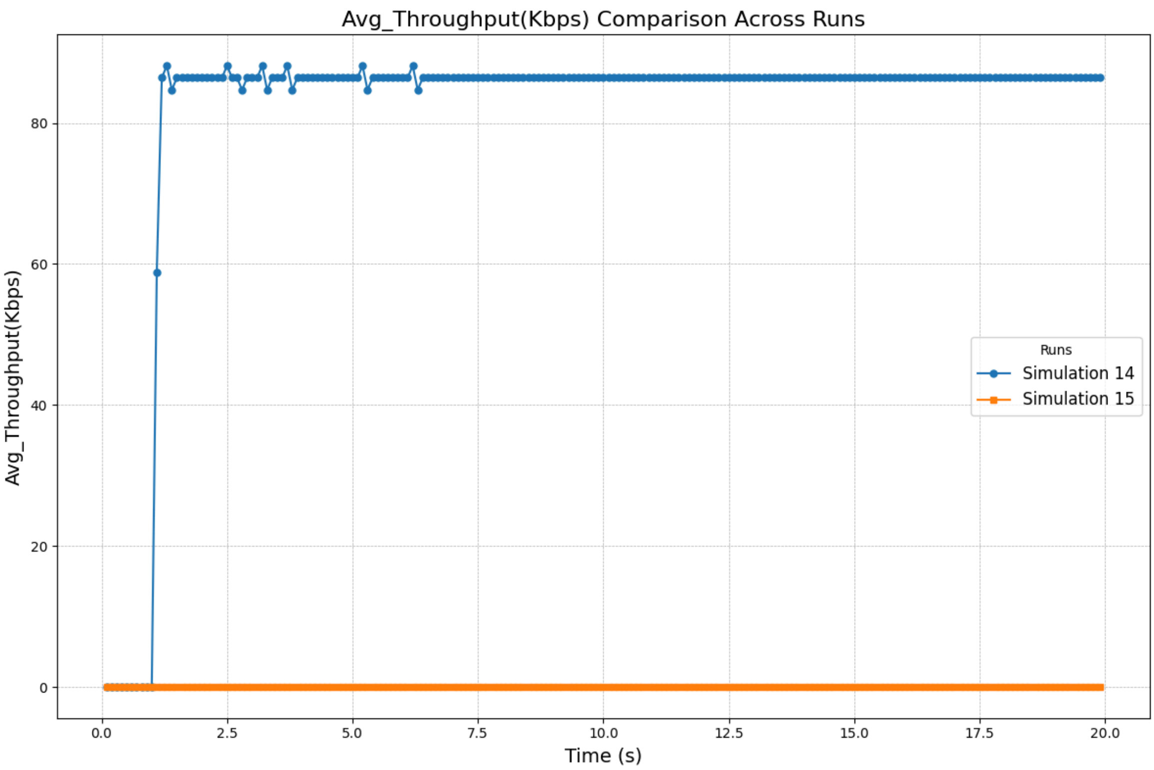
In this set of simulations, the focus was on evaluating the impact of increasing the exponents in the **ThreeLogDistancePropagationLossModel** while keeping the simulation area and other parameters constant.

The simulations were conducted in pairs for comparison:

Parameter	Simulation 13	Simulation 17	Simulation 14	Simulation 15
Area size	5000 m	5000 m	10000 m	10000 m
# of eNodeBs	2	2	2	2
# of UEs	5	5	5	5
Remote Hosts	1	1	1	1
Scheduler	RrFfMacScheduler	RrFfMacSchedule	RrFfMacScheduler	RrFfMacScheduler
Hysteresis Handover	3 dB	3 dB	3 dB	3 dB
Hysteresis TTT	120 ms	120 ms	120 ms	120 ms
Path Loss Model	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance
Path Loss Parameters	Default	Default	Default	Default
- Distance0	50.0 m	50.0 m	50.0 m	50.0 m
- Distance1	100.0 m	100.0 m	100.0 m	100.0 m
- Exponent0	1.7	2.5	1.7	2.5
- Exponent1	2.5	4.5	2.5	4.5
- Exponent2	3.2	7.7	3.2	7.7
Buildings	No	No	No	No
VoIP Codec	G.711	G.711	G.711	G.711
Data Rate (kbps)	64	64	64	64
Packet Size (bytes)	80	80	80	80
Mobility Model	RandomWaypoint	RandomWaypoint	RandomWaypoint	RandomWaypoint
UE Speed (m/s)	10–30	10–30	10–30	10–30
Pause Time (s)	2.0	2.0	2.0	2.0



Average throughputs of Simulation 13 (regular exponents) and SImulation 17 (raised exponents).



Average throughputs of Simulation 13 (regular exponents) and Simulation 17.

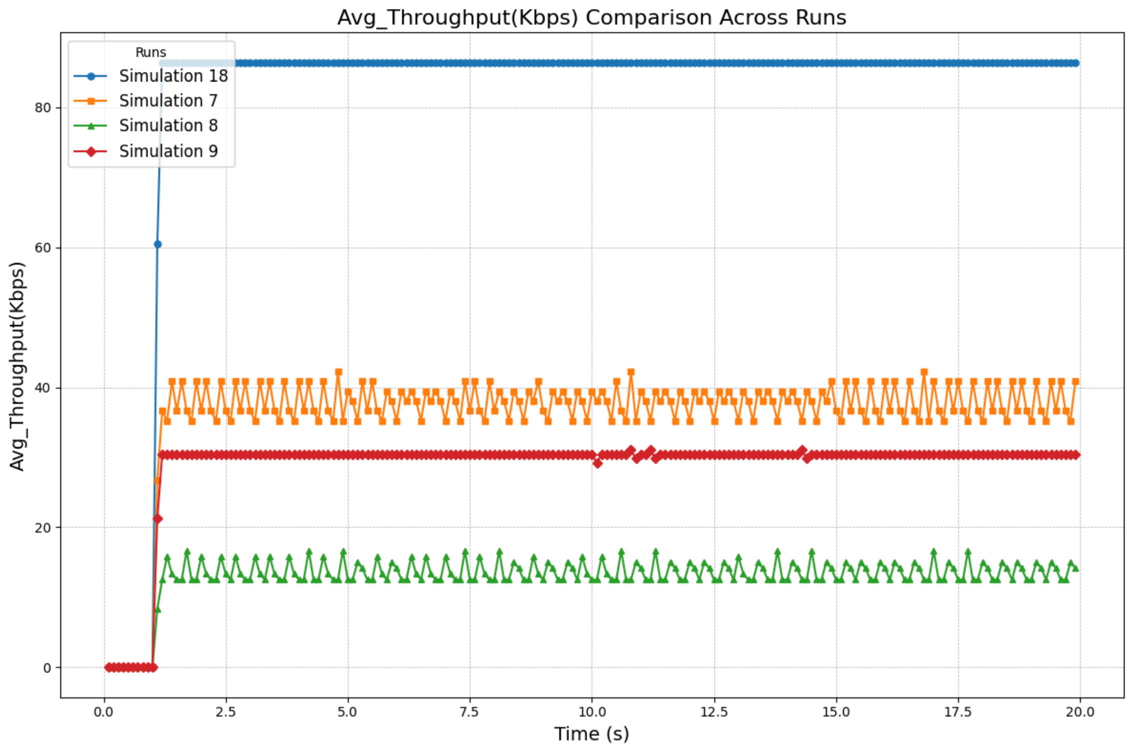
The average throughput results for both pairs of simulations—**Simulation 13** and **Simulation 17**, as well as **Simulation 14** and **Simulation 15**—clearly demonstrate the impact of increasing the path loss model parameters. In both cases, higher exponents in the propagation loss model lead to reduced throughput.This reduction is primarily due to increased signal attenuation caused by the higher path loss exponents, which simulate more severe signal degradation over distance. As a result, the link quality deteriorates, leading to lower data rates and reduced overall network performance.

4.4. VoIP Codec Comparison

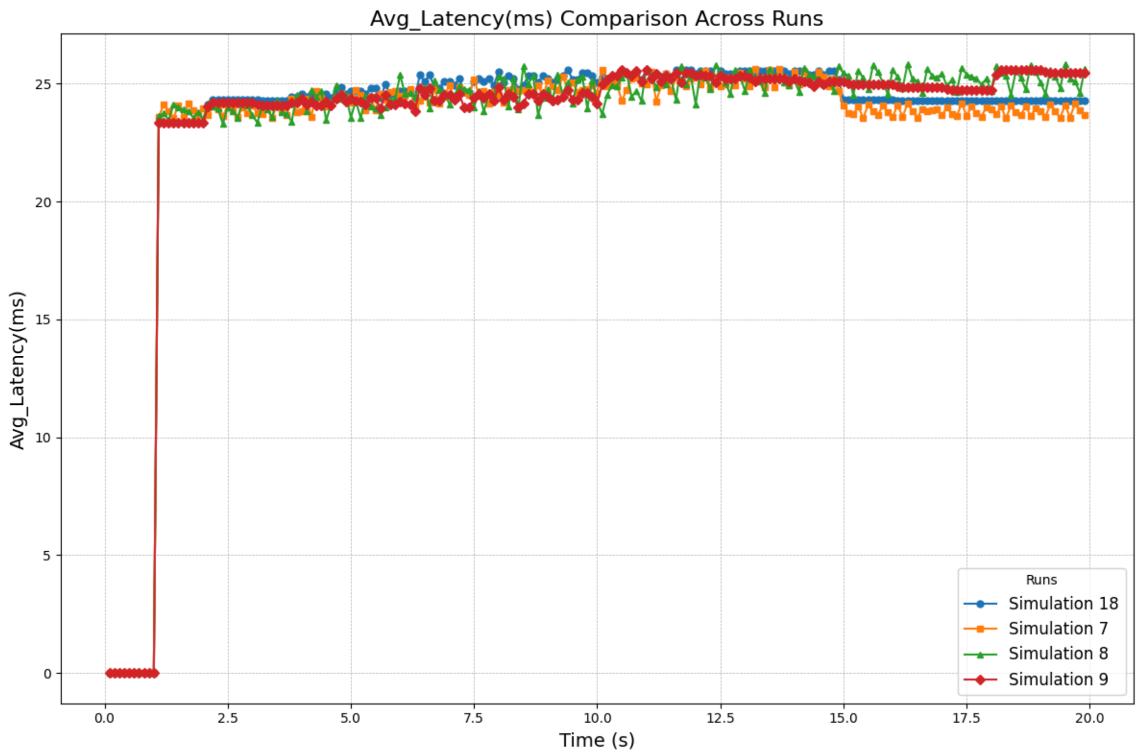
The performance of four different VoIP codecs—G.711, G.722.2, G.723.1, and G.729—was evaluated under identical network conditions to analyze their impact on throughput, latency, packet loss.

- G.711
- G.722.2
- G.723.1
- G.729

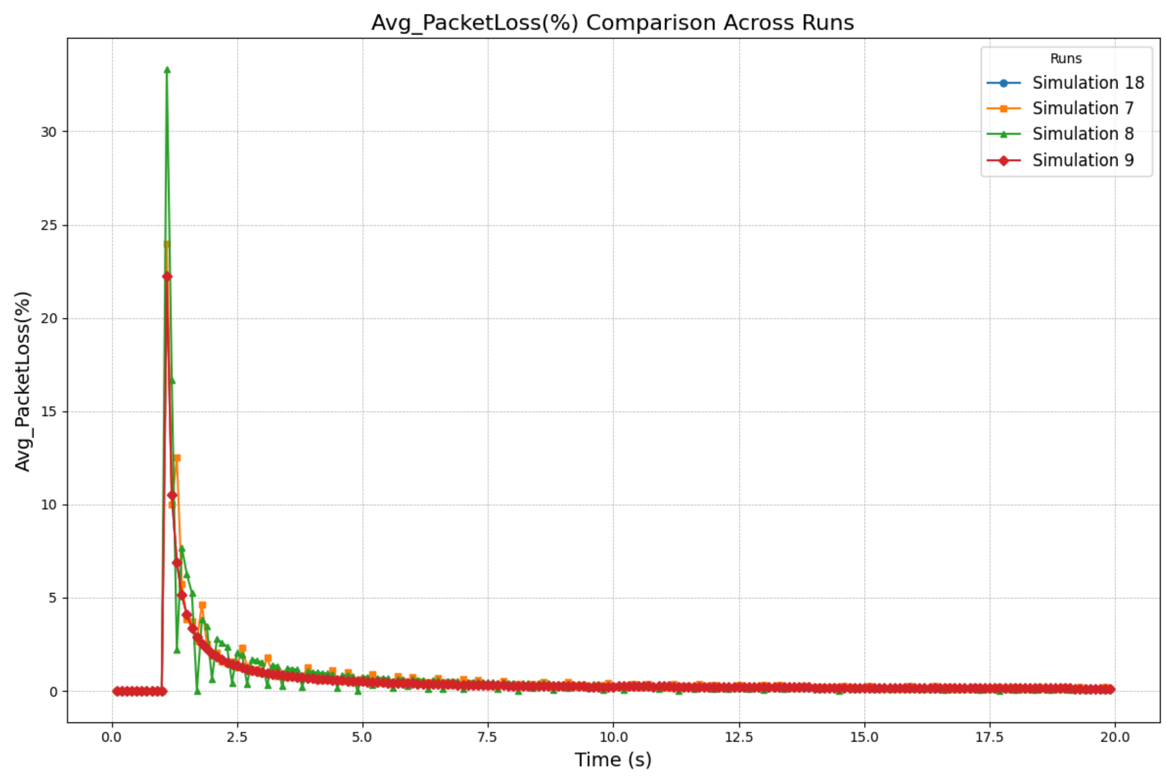
Parameter	Simulation 18	Simulation 7	Simulation 8	Simulation 9
Area size	5000.0 m	5000.0 m	5000.0 m	5000.0 m
# of eNodeBs	2	2	2	2
# of UEs	5	5	5	5
Remote Hosts	1	1	1	1
Scheduler	RrFfMac	RrFfMac	RrFfMac	RrFfMac
Hysteresis Handover	3 dB	3 dB	3 dB	3 dB
Hysteresis TTT	256 ms	256 ms	256 ms	256 ms
Path Loss Model	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance	ThreeLogDistance
Path Loss Parameters	Default	Default	Default	Default
- Distance0	50.0 m	50.0 m	50.0 m	50.0 m
- Distance1	100.0 m	100.0 m	100.0 m	100.0 m
- Exponent0	1.7	1.7	1.7	1.7
- Exponent1	2.5	2.5	2.5	2.5
- Exponent2	3.2	3.2	3.2	3.2
Buildings	No	No	No	No
VoIP Codec	G.711	G.722.2	G.723.1	G.729
Data Rate (kbps)	64	25.84	6.3	8.0
Packet Size (bytes)	80	60	24	10
Mobility Model	RandomWaypoint	RandomWaypoint	RandomWaypoint	RandomWaypoint
UE Speed (m/s)	10–30	10–30	10–30	10–30



Average throughputs of Simulations 18, 7, 8, 9 testing different codecs.



Average latency of Simulations 18, 7, 8, 9 testing different codecs.



Average packet loss of Simulations 18, 7, 8, 9 testing different codecs.

Average Throughput

- **G.711 (Simulation 18):** Achieved the highest throughput due to its high bitrate (64 kbps) and larger packet size (80 bytes).
- **G.722.2 (Simulation 7):** Throughput dropped significantly (37.8891 Kbps) as this codec uses a lower bitrate (25.84 kbps) and smaller packet size (60 bytes).
- **G.723.1 (Simulation 8):** The lowest throughput (13.6536 Kbps), corresponding to its minimal bitrate (6.3 kbps) and the smallest packet size (24 bytes).
- **G.729 (Simulation 9):** Balanced throughput (30.3716 Kbps) due to a moderate bitrate (8 kbps) and packet size (10 bytes).

The differences in throughput are proportional to the bitrate and packet size of the codecs, with higher values enabling more data transmission over the same time period.

Average Latency

All codecs displayed similar latency values. The comparable results indicate that latency was not significantly affected by the codec choice under the tested conditions.

Packet Loss

- **G.711 (Simulation 18):** Lowest packet loss, attributed to its high bitrate and resilience in the network.
- **G.723.1 (Simulation 8):** Exhibited the highest packet loss due to its minimal bitrate, which may struggle to maintain quality in cases of network degradation.

- Other codecs had moderate losses, with **G.722.2** and **G.729** showing slightly better performance than G.723.1.

The results show a trade-off between throughput, quality, and network resource efficiency:

- **G.711** offers the best performance in terms of throughput and minimal packet loss but requires more bandwidth. It is suitable for high-quality audio in networks with ample resources.
- **G.729** strikes a balance between efficiency and quality, a good choice for constrained networks.
- **G.722.2** and **G.723.1** are more efficient in bandwidth usage but come at the cost of reduced throughput and increased jitter.

5. Conclusion

This LTE network simulation project using NS-3 analyzed how various network parameters impact performance metrics like throughput, latency, packet loss, and jitter. Key factors studied included mobility models, MAC schedulers, area size, path loss parameters, and VoIP codecs.

The results highlighted that mobility models strongly affect performance, with random mobility introducing variability and static placements ensuring consistency. MAC schedulers showed minimal differences in scenarios. Larger area sizes and increased path loss exponents led to degraded performance due to signal attenuation. VoIP codec comparisons revealed trade-offs, with high-bitrate codecs like G.711 delivering better throughput but requiring more bandwidth, while low-bitrate codecs optimized resource use at the cost of quality.

Overall, the project demonstrated how LTE network performance depends on the careful tuning of parameters to meet specific requirements, whether for quality, efficiency, or scalability. These findings provide a practical basis for optimizing LTE networks and adapting them for future technologies like 5G.