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# QoE Analysis of DASH in Single-RAT and Multi-RAT Networks

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- Sanjay Chawla

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## ABSTRACT

The rapid adoption and growing traffic volume over cellular Long Term Evolution (LTE) networks have been mounting concerns for network operators, majorly due to the limited capacity and bandwidth of the available spectrum. In recent years, offloading of cellular traffic over unlicensed spectrum has been the focus of many studies and has even led to many commercial deployments. The LTE-WLAN Aggregation (LWA) is a multi-RAT (Radio Access Technology) implementation which allows LTE traffic to utilise Wireless Large Area Network (WLAN) for its traffic flow without significant impact to the existing deployments. LWA can be an attractive investment for operators having well-established deployments in WiFi and LTE markets. Also, with the rising popularity of video-based content, streaming services have emerged to be the largest contributors to the total traffic volume. Providing a high-quality experience to the users has been a significant focus not only for video service providers but also for network operators.

Dynamic Adaptive Streaming over HTTP (DASH) is a standard implementation for adaptive video streaming over HTTP, widely used by many video service providers. In this study, we use an open-source simulation framework, Network Simulator 3 (ns-3) for implementing LTE and LWA networks. Then, by streaming a DASH video over these networks, we analyse the Quality of Experience (QoE) for the users. A set of experiments are performed to understand the impact of different network configurations on a user's QoE. Our findings suggest an improved bitrate performance of video streaming in LWA networks, subject to WiFi contention. Our simulator implementation is further extensible for analysis of multi-cast scenarios and other aggregation solutions like LTE-DC (Dual Connectivity), LTE-NR (New Radio).

**Keywords:** LTE, LWA, Multi-RAT networks, DASH, ns-3

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# Abbreviations

| | |
|---|---|
| 3GPP | The 3rd Generation Partnership Project |
| ABR | Adaptive Bitrate |
| AC | Access Control |
| AP | Access Point |
| CDN | Content Delivery Network |
| CTTC | Centre Tecnològic de Telecomunicacions de Catalunya |
| DL | Downlink |
| DRB | Data Resource Bearer |
| E-UTRAN | Evolved Universal Terrestrial Radio Access Network |
| eLWA | enhanced-LWA |
| eNB | Evolved Node B |
| EPC | Evolved Packet Core |
| EPS | Evolved Packet System |
| GSM | Global System for Mobile Communications |
| HTTP | Hypertext Transfer Protocol |
| IETF | Internet Engineering Task Force |
| IF | Influence Factors |
| IP | Internet Protocol |
| ISO | International Organization for Standardization |
| ISOBMFF | ISO Base Media File Format |
| ITU | International Telecommunication Union |
| LAA | License Assisted Access |
| LENA | LTE EPC Network Simulator |
| LTE | Long Term Evolution |
| LTE-U | LTE-Unlicensed |
| LWA | LTE-WLAN Aggregation |
| LWAAP | LTE-WLAN Aggregation Adaptation Protocol |
| LWIP | LTE-WLAN Aggregation with IPSec |
| MAC | Media Access Control |
| MBMS | Multimedia Broadcast Multicast Services |
| MIMO | Multiple-In Multiple-Out |
| MOS | Mean Opinion Score |
| MPD | Media Presentation Description |
| MPEG | Moving Picture Experts Group |
| MPTCP | MultiPath TCP |
| NS-3 | Network Simulator-3 |

| | |
|---|---|
| OFDMA | Orthogonal Frequency Division Multiple Access |
| PDU | Packet Data Unit |
| PGW | Packet Data Network Gateway |
| PSNR | Peak Signal-to-Noise Ratio |
| QCI | QoS Class Identifier |
| RAN | Radio Access Network |
| RAT | Radio Access Technology |
| RB | Radio Bearer |
| RLC | Radio Link Control |
| RTP | Real-time Transport Protocol |
| SAE | System Architecture Evolution |
| SC-FDMA | Single-Carrier FDMA |
| SMS | Short Message Service |
| SRB | Signalling Radio Bearer |
| SSIM | Structural Similarity Index Measure |
| TCP | Transmission Control Protocol |
| TS | Transport Stream |
| UDP | User Datagram Protocol |
| UE | User Equipment |
| UL | Uplink |
| UMTS | Universal Mobile Telecommunications System |
| VQA | Video Quality Assessment |
| WLAN | Wireless Local Area Network |
| WT | WLAN Termination |

# 1 Introduction

## 1.1 Motivation

The demand for video and streaming media has continuously increased in recent years. This rise in demand for video traffic can be attributed to numerous factors not limited to better processor speeds, improved recording capabilities, low-latency transfer of videos and large scale deployment of wireless infrastructure. According to a recent report by Sandvine [7], 80% of all internet traffic today is video, gaming and social networking (which is also rapidly turning towards video-based content with applications like TikTok and Instagram). Also, HTTP media streams are the highest consumers of downstream bandwidth and combined with Netflix and YouTube traffic contribute to 34% of all downstream internet traffic.

This growth in internet traffic is aggravated by the growing number of cellular phone subscribers. Cisco Annual Internet Report [8] estimates an annual growth of 8% in cellular subscriptions leading to 13.1 billion users by the year 2023. Moreover, 46% of these connections are estimated to be LTE users, which places a challenge for the cellular network operators due to a limited spectrum available to support this growth. Use of MIMO antennas and higher-order modulation is alone not sufficient to provide higher data rates. According to a report by Qualcomm [9], only 16% of operators are capable of achieving Gigabit LTE (peak data rate above 1Gbps) using just their licensed spectrum.

The 3rd Generation Partnership Project (3GPP) has been considering the offloading of cellular traffic to the unlicensed spectrum [10] commonly used in WLAN deployments, especially WiFi. Operation in unlicensed spectrum also offers high bandwidth and capacity. Moreover, WiFi has seen high adoption in many residential and industrial deployments as well as cellular devices, making it suitable for LTE-WLAN interworking solutions. LTE operation in unlicensed spectrum forms a crucial part of the 5G road-map [9] in terms of its rapid deployment and high compatibility to existing devices. Despite the cost and performance benefits, the use of Unlicensed spectrum for LTE comes with various protocol and coexistence restrictions.

Some major implementations of LTE in the unlicensed spectrum include: Licensed Assisted Access (LAA) [11], LTE-Unlicensed (LTE-U) [12], LTE-WLAN Aggregation (LWA) [13], LTE-WLAN Radio Level Integration (LWIP) [13], MuLTEFire [14] and Multipath Transmission Control Protocol (MPTCP) [15]. Each implementation uses a different technique to establish a shared channel between LTE and WiFi. A comparison of LWA network performance against LAA and other LTE deployments in the unlicensed spectrum has been performed by Sirotkin [16] and 4G Americas [17]. The results signify that LWA offers performance comparable to LAA and the possibility of more improvements in eLWA (enhanced-LWA introduced in 3GPP Release 14). Moreover, LWA offers possibility of easier adoption due to its low impact on existing deployments. Thus, it becomes crucial to analyse the performance of LWA deployments.

At the same time, many streaming solutions nowadays rely on HTTP as their application protocol. Dynamic Adaptive Streaming over HTTP (DASH) has emerged to be a popular standardised solution for many service providers. In the case of video streaming solutions, network performance traffic metrics like throughput, delay and jitter are not entirely reflective of the user experience [18]. This limitation has led to a shift towards Quality of Experience (QoE) becoming the metric of choice for various service and network designers.

As will be discussed in Section 2.5, there have been limited studies that analyse QoE for realistic (multi-user) network deployments. This motivates our first step towards analysing QoE for multiple DASH clients in an LTE deployment. We then extend our implementation to support DASH streaming for LWA deployments. We are thereby addressing the gap between a growing interest in LWA network optimisations and lack of open-source simulators. Besides, the implementation can easily be extended to study other aggregation solutions like LTE-DC (Dual Connectivity) and LTE-NR (New Radio) as well as to test network optimisation strategies.

## 1.2 Research Objectives

The objectives of our research are as follows:

- Building a simulator for DASH that supports realistic LTE scenarios
- To study the influencing factors (IF) and models for QoE. Use the simulator to analyse the IF under different network deployment scenarios
- Understanding the operation of LWA and analyse the resulting video streaming performance
- Use an open-source simulation framework, making it extensible for broader study

and research

The simulator has been implemented in Network Simulator-3 (NS-3) [19] as it is a widely used, publicly available (under GNU GPLv2 license) software simulation framework used for designing and testing complex network scenarios.

## 1.3 Outline

The remaining chapters of the thesis are arranged as follows: In chapter 2, we provide a conceptual overview of the technologies involved and related work. Chapter 3 discusses simulator implementation. The results of different scenarios have been categorically presented and discussed in chapter 4. Chapter 5 concludes the research and provides the scope for future work involved.

# 2 Background

This chapter provides a conceptual overview and background for technologies relating to the study. The initial sections give a brief overview of LTE and LWA. Followed by a discussion of video streaming and DASH. We then briefly explore the QoE measurements. In the end, we describe the related works in LTE and LWA network simulations.

## 2.1 Long Term Evolution (LTE)

Long Term Evolution (LTE) or Evolved Universal Terrestrial Radio Access Network (E-UTRAN)[20] was a culmination of standardisation efforts towards achieving higher data-rates, improved spectral efficiency, lower RAN latency and high scalability. LTE provided an upgrade path for the third generation cellular networks, GSM and UMTS. LTE specifications were finalised in 3GPPs Release 8 [20] with further addition of new spectrum bands in Release 9 [2]. Although a complete description of LTE is beyond the scope (refer [21], [22]), we include some concepts related to our study.

### 2.1.1 Evolved Packet System (EPS)

EPS is an all-IP system connecting a mobile user to an external data network and cellular services like voice calls and SMS. EPS consists of a core and access network implemented by SAE [23] (mainly consisting of EPC [24]) and LTE respectively. All data communications in EPS can be split into U-plane (for user data) and C-plane (for signalling/control data). Figure 2.1 depicts core EPS entities and interfaces connecting them.

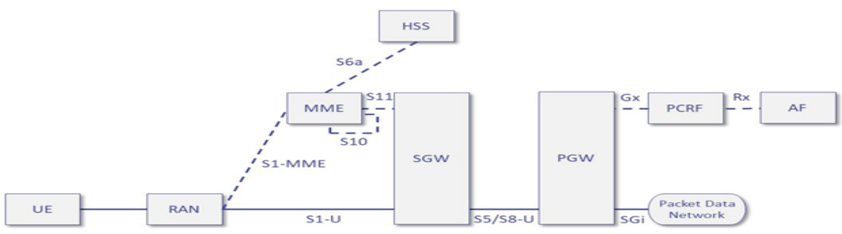



Figure 2.1: Simplified EPS Architecture

### EPS Bearer and Radio Bearer

Due to the large variation in channel and network conditions, it is difficult to ensure a steady flow of traffic through the EPS network. However, certain traffic flows need to be prioritised and delivered with respective Quality of Service (QoS). EPS ensures this by establishing multiple EPS Bearers between each UE and PGW inside an EPS network. All IP traffic is associated with a specific bearer having a QoS Class Identifies (QCI) [25] that determines QoS policies and maintains it according to the priority, acceptable packet loss, delay and bitrate policy as shown in Figure 2.2.

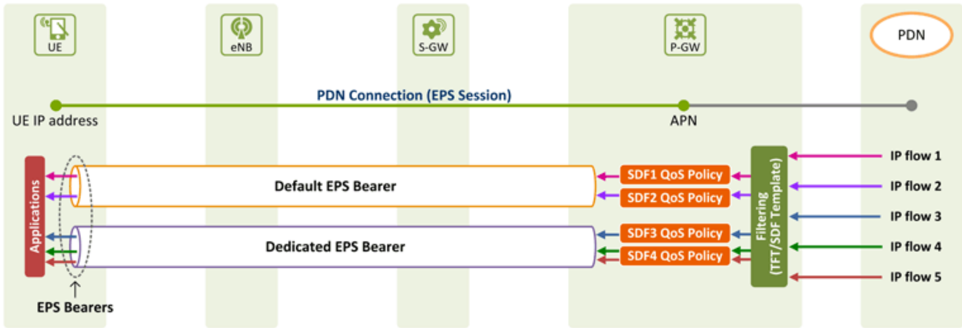



Figure 2.2: EPS Bearers and IP traffic flow [1]

A default bearer is established when a UE is attached and provides best-effort delivery of packets across the network. A dedicated bearer, on the other hand, is established after attachment when requested by certain applications. As each EPS bearer manages flow across different interfaces in the EPS network, it can be broken down into respective component bearers.

A Radio Bearer is the flow of traffic between UE and ENB. The radio bearer can be split into signalling radio bearers (SRB0, SRB1) and data bearers (DRB identified by DRB ID). Based on the QCI associated with the bearer, the MAC and RLC layers at LTE are configured.

## 2.1.2 LTE Operation

The architecture of LTE consists only of Evolved Node B (eNB) entities, interconnected with each other over X2 interfaces and with EPC over S1 interface, as shown in Figure 2.3. Each eNB is connected to multiple UE over the Uu interface. Each UE connection with an eNB consists of a downlink and an uplink radio link. LTE deployments can either support Time Division Duplex (TDD) or Frequency Division Duplex (FDD) operation.

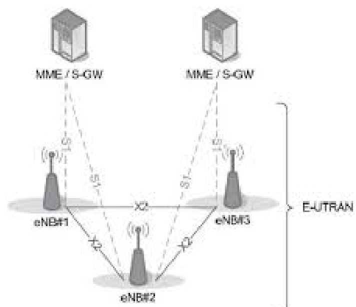



Figure 2.3: LTE Architecture. [2]

When operating using TDD, a single allocated band is time segmented to send and receive data. In FDD operation, the UE is allocated two different frequency bands for uplink and downlink. The physical channel for the Uu interface operates in licensed spectrum bands (ranging between 700MHz to 2.6GHz). The specific band allocation varies geographically and based on the mode of LTE operation (TDD or FDD).

LTE in downlink uses Orthogonal Frequency Division Multiple Access (OFDMA) which allows the use of OFDM for multiple access in a time-frequency domain. The specified bandwidth for channels is 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz, and 20MHz with a fixed sub-carrier spacing of 15kHz. A resource block (RB) is the smallest unit of allocation, composed of 12 sub-carriers in frequency and contains seven symbols (one slot). Resource consumption can be measured in terms of number of RB available (or used) at eNB. In the uplink, a single carrier is required unlike N carriers in the downlink. Thus, the use of SC-FDMA results in reduced peak-to-average power ratio (PAPR) and power efficiency at the UE. Additionally, with the use of higher-order MIMO configuration, LTE is able to achieve better spectral efficiency or higher throughput [26].

### 2.1.3 LTE Protocol Stack

#### Access Stratum and Non-Access Stratum

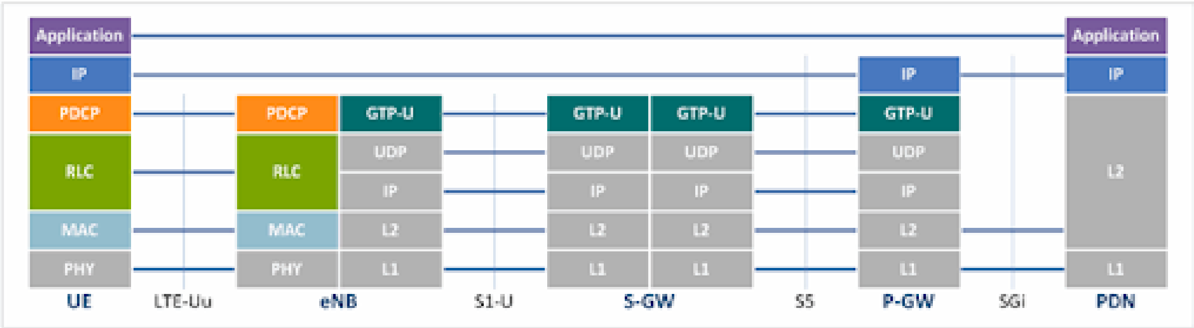
LTE Protocol stack consists of Non-Access Stratum (NAS) and Access Stratum (AS) layers. The NAS acts at the Network Layer to establish a connection to the core network and is responsible for controlling the transfer and radio resources. The AS layer acts at the link layer and is responsible for the actual transfer of both user and control data. The AS layer is further divided into three sub-layers, layer-1 (L1) consisting of PHY layer, layer-2 (L2) composed of MAC, RLC and PDCP layers and layer-3 (L3) composed of RRC layer.

#### User Plane and Control Plane

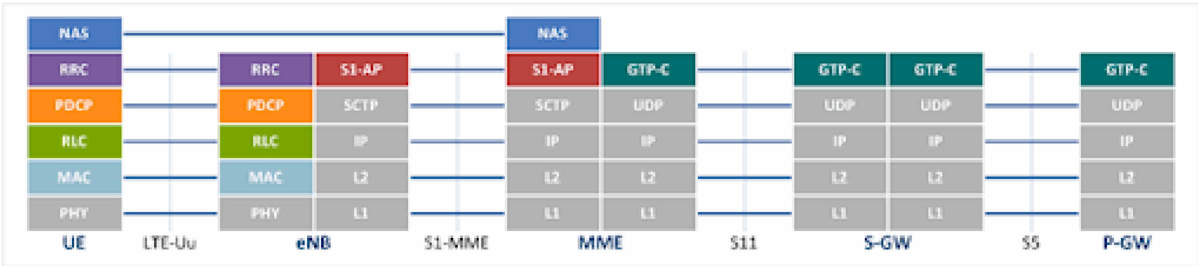
The user and control data flowing through the EPS network follows a different set of protocols. Both the user and control plane stacks are shown in Figure 2.4a and Figure 2.4b respectively.

*User Plane:* The terminal nodes for user data are the UE and the external PDN. The data transmission through eNB, SGW and PGW use a GTP tunnel (using UDP/IP) for transmission, whereas at the LTE-Uu interface uses PDCP, RLC and MAC protocols.

*Control Plane:* The control data flow between each UE and PGW. Similar to user data, a GTP-C tunnel exists except that it terminates at MME. A NAS connection is established




(a) User Plane




(b) Control Plane

Figure 2.4: EPS Protocol Stack [1]

between the UE and MME over LTE-Uu and S1-MME interface. S1 interface user SCTP protocol between eNB and MME. LTE-Uu interface is similar to user data but uses RRC and NAS protocols for configuration of radio channels and network parameters.

### Protocols

Protocols at the LTE-Uu interface are described below:

- NAS [27]: Two major functions of the protocol are mobility management (establishing UE-EPC connections) and session management (setup and maintenance of EPS Bearers). It also handles the authentication, security and idle-mode operations.
- RRC [28]: The main function is the transfer of NAS signalling. Next, it establishes and configures all below layers based on the control data. It is responsible for radio bearer configuration on and after UE attachment, i.e. SRB and DRB configuration.
- PDCP [29]: The PDCP protocol handles the efficient transfer of user data IP packets. It handles data integrity and buffering during handover as lower layers are reconfigured. Additional tasks include header compression and AS security.
- RLC [30]: RLC protocol handles packets from upper layers by segmenting and transmitting. On reception from lower layers, it handles reordering, duplicates and requesting re-transmission of segments. Depending on the desired reliability configured during setup, RLC can operate in three modes, namely acknowledged

mode (AM), an unacknowledged mode (UM) or transparent mode (TM).

- MAC [31]: This layer forms the interconnection of logical channels and transport channels. This essentially means mapping higher level PDUs to Transport Blocks, i.e. multiplexing and de-multiplexing of data. At eNB, MAC handles dynamic scheduling of resources to maintain QoS for each logical channel. It also performs error correction on received SDUs

- PHY [32]: Handles the physical channel aspects like modulation, power control, duplexing and error correction.

## 2.2 LTE-WLAN Aggregation (LWA)

Introduced in 3GPP's Release-13 specification, LWA allows for simultaneous transfer of data between eNB and configured UE devices over both LTE and WLAN (most commonly, WiFi) radio resources. Although the splitting was originally supported only in the downlink, it was enhanced (eLWA) to support uplink aggregation, along with the addition of 60GHz (WiGig) support with up to 2GHz bandwidth, mobility management and other enhancements. As of early 2019 [33], Taiwan has one launched LWA network, two operators investing in South Korea and Taiwan.

If the user device supports simultaneous connections over LTE and WiFi, LWA provides users with better throughput and seamless experience as it automatically selects the best channel for transmission. If simultaneous connections are not supported, the user can select appropriate connection without any interruptions to applications connected to the internet. Besides the obvious advantage of increased user capability, LWA deployment requires minimal upgrades and regulatory clearances. The WiFi AP devices used can simultaneously transfer LTE and WiFi, based on channel availability making LWA friendly to existing operations.

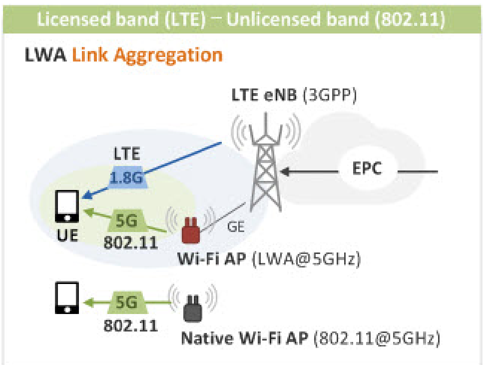



Figure 2.5: LWA Setup [3]

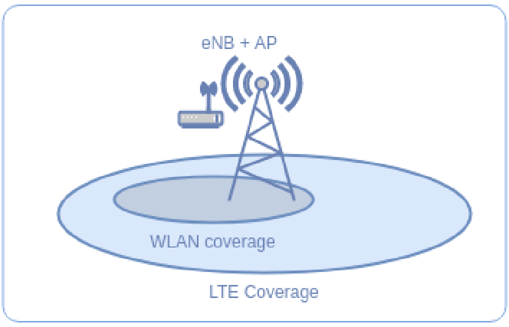
Figure 2.5 shows a basic LWA setup.

### 2.2.1 Deployment

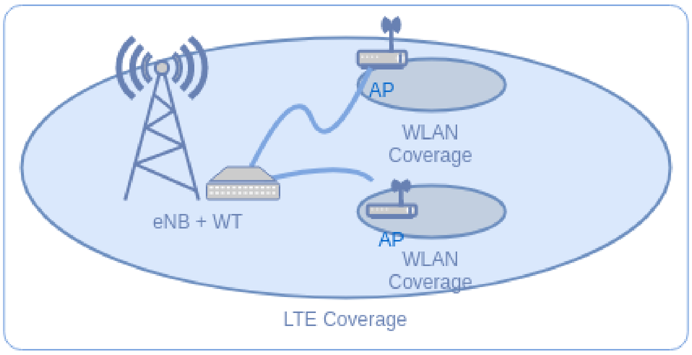
LWA supports two deployment scenarios:

1. Collocated Deployment:

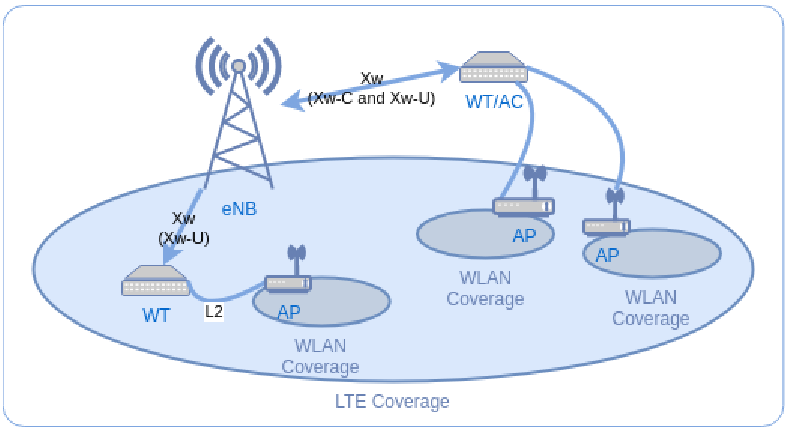
   When the backhaul connection between the eNB and WLAN is ideal or internal to eNB. This deployment means that the WiFi AP is collocated at the eNB. The interface between LTE and WLAN, in this case, is up to the implementation. This scenario is particularly used for small/femtocell deployments.




(a) *LWA Collocated:* Ideal/Internal backhaul




(b) *LWA Non-Collocated:* WT integrated with eNB




(c) *LWA Non-Collocated:* Standalone WT or integrated with AC

Figure 2.6: LWA Deployment Scenarios

2. Non-Collocated Deployment:

   When the backhaul connection is non-ideal. In this case, a logical WLAN Termination (WT) node is connected to the eNB over Xw interface. A single eNB can connect to multiple WT nodes. Since WT node is logical, place of implementation of WT is not specified [13]. Further multiple deployment scenarios can exist depending upon the WT implementation:

   - The WT implementation is integrated into eNB and WT is connected to multiple WiFi Access Points (AP) over a layer 2 (L2) network like Ethernet
   - When WT is implemented as a standalone device, it supports user plane data over the Xw-U interface. APs are connected to WT over a L2 network.
   - If the existing WiFi setup consists of an Access Control (AC), the WT can

be implemented such that it supports GTP-U protocol for user plane data (Xw-U) and Xw-AP protocol for LWA control data (Xw-C).

Figure 2.6 on page 9 shows collocated and non-collocated deployment scenarios.

### 2.2.2 LWA Operation

LWA implementation is similar to the Dual Connectivity (DC) operation used for connecting a UE to multiple eNB devices simultaneously [34]. The main components for operation are LWA eNB and LWA UE. When user data on LWA configured bearer arrives at the eNB, data is split at the PDCP layer of LTE, some fraction of packets are passed unaltered to RLC for transmission over LTE radio. The remaining packets are passed to a new LTE-WLAN Aggregation Adaptation Protocol (LWAAP) entity [35], which adds a new header mapping the DRBID (corresponding to the bearer) and the ether-type to LWA (0x9E65 [36]). The LWAAP packets are then delivered to WT via Xw interface which then allows sending it over the 802.11 radio by the WiFi AP.

At the receiving LWA configured UE, LWAAP entity corresponding to the one at eNB receives WiFi packets intended for LWA using ether-type, decodes the bearer using DRBID and sends the PDCP SDU to the PDCP layer of LTE. Here, the PDCP layer reorders the PDCP packets from RLC and the ones from WiFi and sends them to the upper layers. Figure 2.7 shows the protocol stack for a non-collocated deployment.

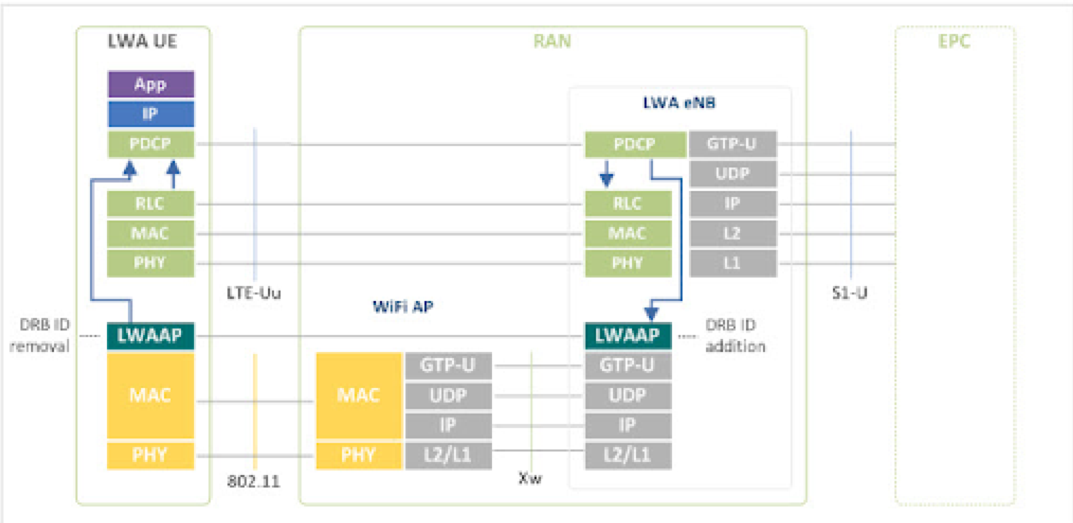



Figure 2.7: LWA User Plane Protocol Stack (Non-Collocated Deployment) [3]

Based on the splitting of data at eNB, bearers can be configured as LTE bearers, Split LWA Bearer or Switched LWA Bearer as seen in Figure 2.8. This bearer level splitting provides high throughput gains for applications having dedicated IP flows, e.g. video streaming. Irrespective of the bearer state, applications are delivered ordered packets and can work without any interruptions.

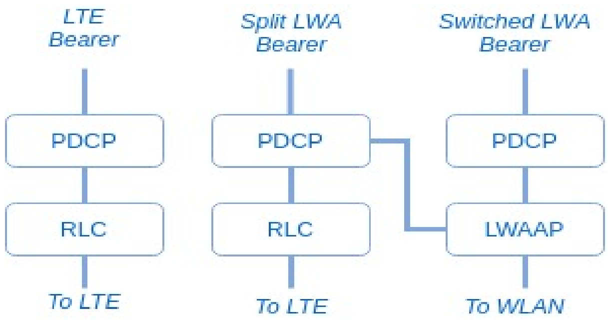



Figure 2.8: LWA Bearers: LTE, Split and Switched

Throughout the LWA operation, eNB handles the configuration of LWA bearers depending on WLAN reported measurements [28]. Based on LTE and WLAN measurements, eNB can decide a better-suited interface for transmission and change bearers accordingly. This automatic switching makes LWA operation transparent to the user simultaneously providing better throughput. Moreover, eNB uses a WLAN Mobility Set which configures the UE to connect to corresponding APs during mobility without notifying the eNB [16].

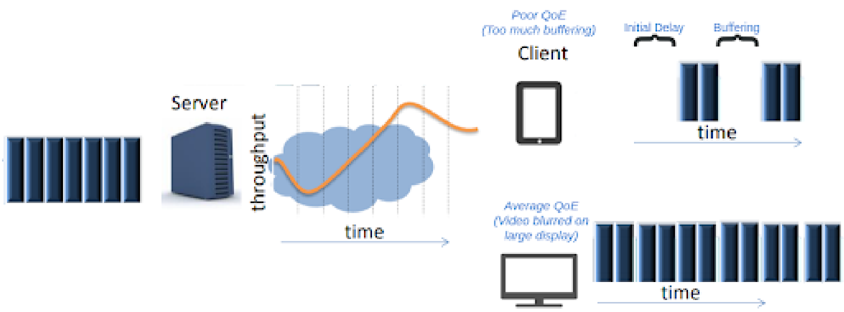
## 2.3 Video Streaming

Streaming of video content is a multi-stage process starting with the high-bitrate recording of original content, encoding using codecs, containerisation and network delivery through Content Delivery Networks (CDNs) and media servers. For our study, we primarily focus on network delivery.

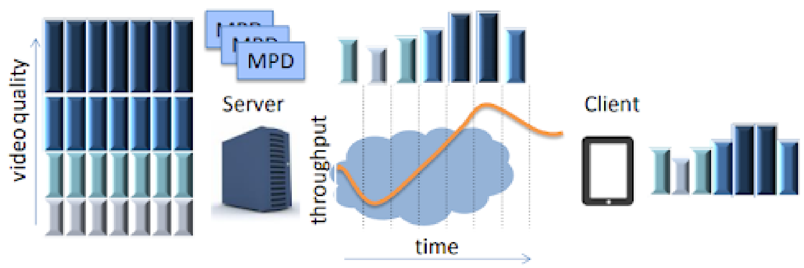
### 2.3.1 Progressive Streaming and Adaptive Streaming

Historically, protocols like Real-Time Protocol (RTP) over User Datagram Protocol (UDP) were preferred for real-time streaming due to lower delays. However, HTTP became the protocol of choice for streaming due to its popularity and resistance to security obstacles like firewalls and NATs. The re-transmission delay and throughput variations in Transmission Control Protocol (TCP) were handled using **progressive downloads**. Similar to file transfer, a media file (whole or in part) is downloaded to the client and playback starts once the download completes. However, progressive downloading can not adapt to client device resolution and network conditions. As a result, cellular devices may suffer from excessive buffering, whereas high-resolution experience blurred video output.

**Adaptive Streaming**, on the other hand, uses multiple versions of the same video file.




(a) Progressive Streaming




(b) Adaptive Streaming

Figure 2.9: Client video reception in Progressive and Adaptive Streaming

An encoder at the server processes a high bitrate video file and converts it into multiple variable bitrate files. The client device can demand an appropriate version based on the display resolution, network and playback performance. This switching is handled without any user intervention and provides a better user experience in poor channel conditions. Both progressive and adaptive streaming find their application in modern applications but later is widely considered for mobile and responsive scenarios.

Figure 2.9 depicts the delivered video output with changing channel conditions (throughput).

### 2.3.2 DASH

Over the years, many vendor-specific implementations of adaptive streaming protocols have been developed. These include Dynamic HTTP Streaming (HDS) by Adobe, HTTP Live Streaming (HLS) by Apple and Microsoft Smooth Streaming. However, these solutions being proprietary with support for different media formats, required the clients to support all format. Dynamic Adaptive Streaming over HTTP (DASH or MPEG-DASH) is a standard adaptive bitrate HTTP-streaming solution developed by Moving Picture Experts Group (MPEG) [37]. It supports streaming over HTTP networks similar to conventional HTTP client-server model for web pages. These technologies which use HTTP for streaming are collectively referred as HTTP adaptive streaming (HAS) or HTTP adaptive bitrate streaming (HABS). DASH has been widely adopted by the industry, e.g. AWS CloudFront CDN, streaming servers, client players like VLC, Shaka and libraries like libdash. Under their partnership with MPEG, 3GPP adopted DASH specifications for wireless usage [38].

### Working

The core operation in DASH is a client requesting a media segment over HTTP GET and the HTTP response to it by the DASH Server. The client decodes the segment, stores in a buffer and processes the media once it has sufficient buffer levels. In order to facilitate the client with appropriate request URLs and media player settings, a Media Presentation Description (MPD) file is first shared with the client. This MPD file contains media information like segment timings, formats and encoding as well as accessibility information like resolution, minimum and maximum bandwidth requirements, digital rights, URLs and other content characteristics. Based on this MPD file, clients can initiate segment requests from the server. Figure 2.10 shows the architecture of a DASH server and client setup.

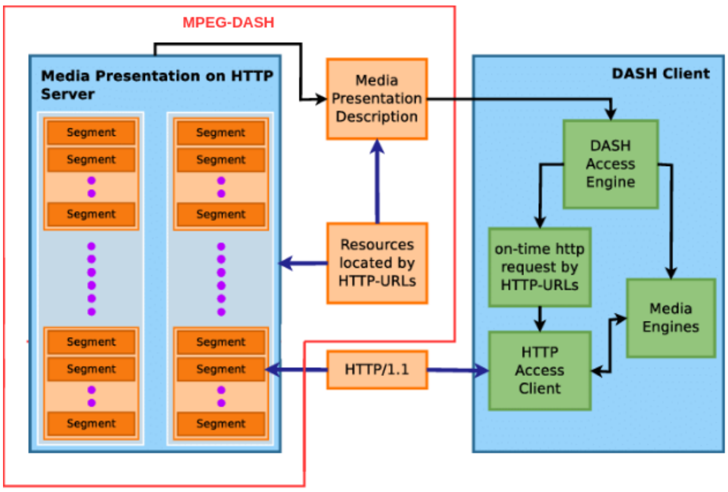



Figure 2.10: DASH Server-Client Architecture [4]: Red outline marks the scope of MPEG-DASH specification

The MPEG-DASH specification provides the MPD file format, and the server segment response for HTTP GET requests. The transfer of the MPD file and the client functionality is open to implementation, making the client implementation flexible depending on its usage, as it controls the playback, buffer levels and segment adaptation.

### Media Presentation Description (MPD) and Segments

MPD is an XML documented file providing media, content and playback related information to the DASH client. DASH data model follows hierarchical structure making XML a suitable format for representing various components.

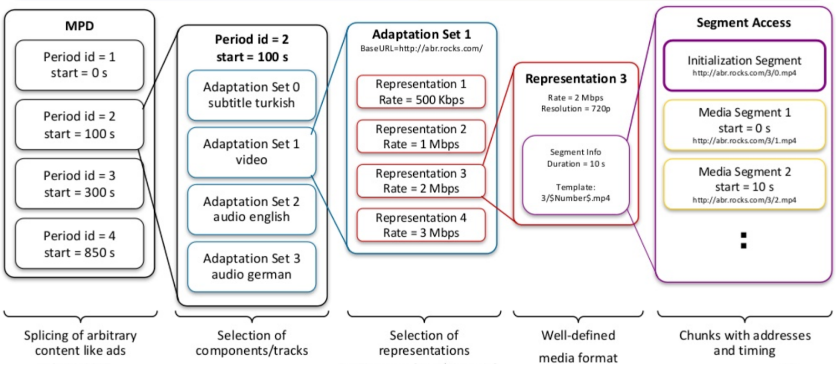
- At the first level of the hierarchy, MPD consists of multiple periods with a specified duration and start times. Periods divide the playback into multiple temporal parts, e.g. placing advertisement after 10 mins of playback
- Single period can further consist of Adaptation Sets. These define separate media components like audio, video and subtitles. Not all adaptation sets are necessary for playback and are usually configurable by the client as well as the user.
- Representations in an Adaptation set consist of multiple versions of the same media content. Each representation is associated with a resolution (width and height) and bandwidth(s) for respective resolution. Based on the client adaptation algorithm, specific representations are requested. This choice may or may not be configurable by the user.
- Segment tags are related to actual segment files required for playback. Depending on the media content (single or multiple segments), its duration (fixed or variable duration) and type of playback (on-demand or live stream) the structure of MPD may change. Nevertheless, it enables the client to form an HTTP URL with a byte-range to fetch segments for playback.

A segment is the body of HTTP GET response from the DASH server. The first segment is the initialisation segment meant for clients to initialise its media decoder. Followed by actual media segments for buffering and decoding. MPEG-DASH describes the ISO Base Media File Format (ISOBMFF) and MPEG-2 Transport Streams (TS) container formats. Moreover, MPEG-DASH does not restrict media codec formats and supports H.264, VP9, HEVC/H.265 and more.

Figure 2.11 represents the MPD hierarchy and sample XML snippet. A detailed description of MPD file and segmentation can be found in [40], [41].

### Adaptation Algorithms

Providing the best possible reconstruction of original media content for the user lies at the core of DASH client applications. Each client implementation uses an algorithm to decide the representations to request for upcoming segments based on some measured or estimated parameters. These algorithms are commonly referred to as Adaptation Algorithms or Adaptive Bitrate (ABR) Algorithms. The most common goals for the client are to maximise the network bandwidth efficiency, minimise re-buffering, maximise




(a) MPD Hierarchy [39]


```
–<MPD minBufferTime="PT1.500000S" type="static" mediaPresentationDuration="PT0H9M56.46S" profiles="urn:mpeg:dash:profile:isoff-on-demand:2011">
 +<ProgramInformation moreInformationURL="http://gpac.sourceforge.net"></ProgramInformation>
 –<Period duration="PT0H9M56.46S">
   –<AdaptationSet segmentAlignment="true" group="1" maxWidth="480" maxHeight="360" maxFrameRate="24" par="4:3" subsegmentStartsWithSAP="1">
     –<Representation id="320x240 46.0kbps" mimeType="video/mp4" codecs="avc1.42c00d" width="320" height="240" frameRate="24" sar="1:1" startWithSAP="1" bandwidth="45652">
        <BaseURL>bunny_45652bps/BigBuckBunny_2snonSeg.mp4</BaseURL>
       –<SegmentBase indexRangeExact="true" indexRange="885-4504">
          <Initialization range="0-884"/>
        </SegmentBase>
      </Representation>
```


(b) Sample MPD file

Figure 2.11: MPEG-DASH MPD file

stability and maintain fairness across devices during bottlenecks (although not all can be achieved simultaneously).

The topic of adaptation algorithms has been widely studied [42] [43], and many algorithms have been proposed and implemented. These algorithms can be broadly classified into the following major categories:

1. *Rate/Throughput Based Algorithms:* These algorithms try to attain maximum bandwidth efficiency by using throughput or bandwidth calculations. In the simplest form, the next representation is selected based on the current segment bitrate to maintain a constant buffer level. This estimation, however, is not very efficient and playback is susceptible to On-Off (Oscillation) effect. To overcome this, some algorithms like Fair, Efficient and Stable adapTIVE (FESTIVE) [44] use randomised scheduling of requests. While Probe And Adapt (PANDA) [45], improves bandwidth estimation using TCP-like network probing mechanism then applying a smoothing function over throughput for the last 20 seconds, quantising the output and scheduling of requests.

2. *Buffer Based Algorithms:* Buffer based approach uses the client buffer level/occupancy to estimate bitrate for the next segment. These algorithms have an advantage in multi-client networks as they do not rely on inaccurate bandwidth estimates. Buffer Based rate selection Algorithm (BBA) [46] defines a rate-map where the lowest bitrate is requested until a threshold occupancy is filled, and the highest

bitrate is requested post the maximum occupancy. Otherwise, any function can be applied for bitrate selection, maintaining threshold occupancy. Buffer Occupancy Based Lyapunov Algorithm (BOLA) [47] uses utility theory to estimate bitrate using a configurable trade-off to jointly maximise the average bitrate and minimise re-buffering duration. The online control algorithm presented using Lyapunov optimisation techniques, is configurable for various content lengths and parameters. BOLA has been implemented in open-source DASH client *dash.js* [48].

3. *Hybrid/Mixed Algorithms:* These algorithms use a combination of metrics like bandwidth, buffer level, segment and re-buffering duration for bitrate estimation. An example of this can be found in MPC [49] where control theory paradigm is applied to select bitrate based on bandwidth predictions, buffer occupancy and dynamics. The MPC algorithm work by looking ahead a few steps (look-ahead horizon), solving the QoE maximisation problem using an estimated bitrate and applying the feedback to the initially estimated bitrate. The process is then iterated for each step. FastMPC and RobustMPC [50] are implemented and tested variations in *dash.js*.

4. *Markov Decision Process (MDP) Based Algorithms:* The adaptation algorithm is modelled as an MPD process where the algorithm learns from long-term rewards of its actions. These algorithms too are iterative, but instead of predicting future estimates, it gradually adjusts the adaptation policy through dynamic programming and deep learning techniques. Deep Q-Learning framework for DASH (D-DASH) [51] is a reinforcement learning algorithm which uses deep neural networks to deal with large state-space of corresponding MDP effectively. This approach makes convergence faster and improves the runtime performance of the algorithm.

Some comparison between these algorithms can be found in respective studies. A comparison of some of the above-discussed algorithms in WiFi and Mobile networks can be found in [52] and [53], respectively. Besides these client-based algorithms, many server-based and network-based adaptation algorithms have been developed, and a detailed survey can be referred to in [43].

## 2.4 Quality of Experience (QoE)

The term QoE was introduced to extend the notion of quality from network-centric QoS to include media and other factors affecting user experience. The definition first proposed in [18] states "Quality of Experience (QoE) is the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user's personality and current state." This definition has been widely adopted and stated in the International Telecommunications Union -Telecommunication Sector (ITU-T) recommendation P.10/G.100 [54]. QoE has been a subject of many recent studies and is an emerging field for video streaming performance analysis. ITU recently standardised the recommendations for a parametric bitstream-based model for quality assessment in progressive and adaptive streaming in ITU-T P.1203 [55].

### 2.4.1 QoE Influence Factors (IF)

Any aspect of the user, system, context or content setting that causes an impact on users experience can be an Influence factor (IF) for the QoE. The above mentioned four categories of influence factors are defined in [56]. Seufert et al. [5], however, categorise the influence factors into technical and perceptual factors. The technical factors are directly related to the operation of the system but are transparent to the user. However, perceptual factors are dependant on technical factors but are directly perceived by the user. Figure 2.12 shows the further categorisation of perceptual and technical factors.

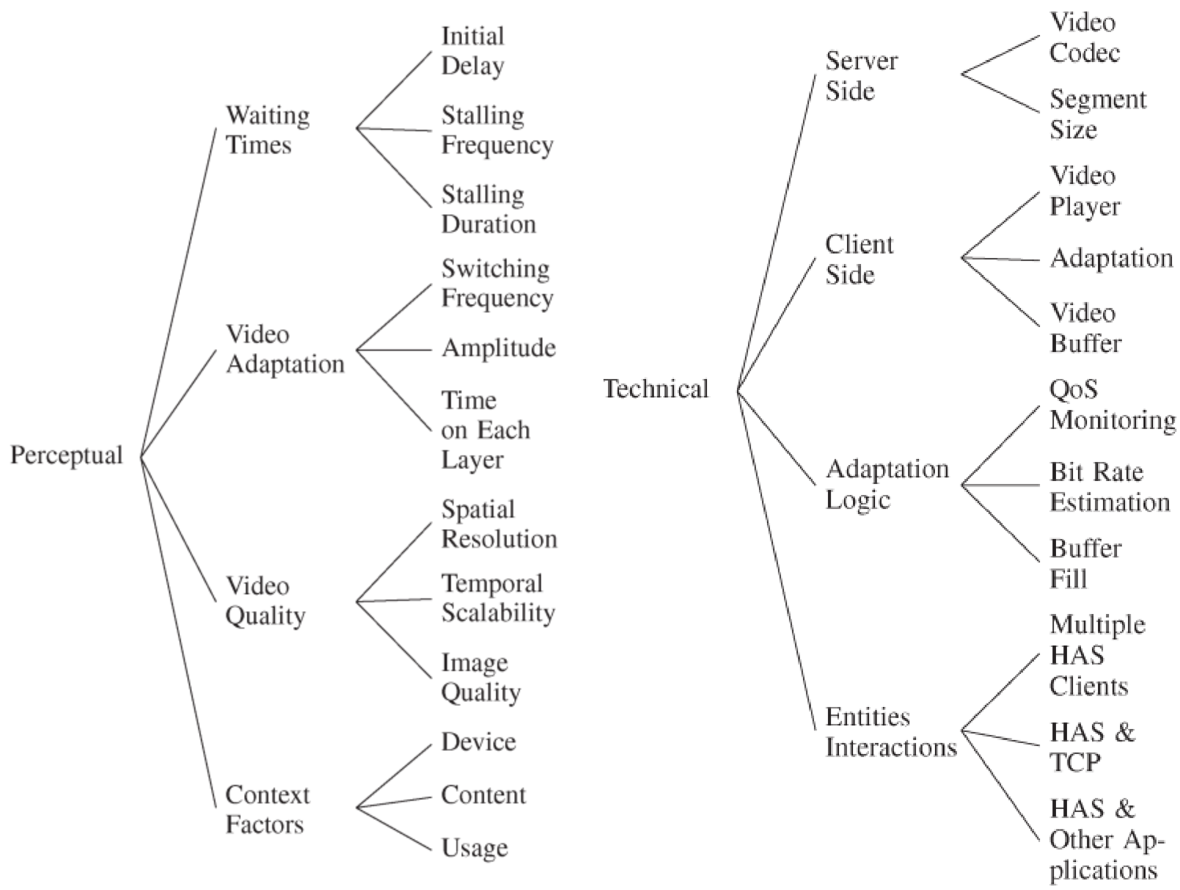



Figure 2.12: Perceptual and Technical Influence Factors [5]

Below, we describe some of the relevant influence factors:

- *Initial Delay*

  It is the playback start duration (usually in seconds). It can also be considered as the duration between a user expressing an intent to watch the video and rendering of the first frame. Every client tries to achieve certain buffer threshold before initiating playback to avoid interruptions due to short-term variations in reception. The initial threshold needs to maintain a trade-off in order to provide a shorter initial delay and avoid future interruptions. Hoßfeld et al. [57] indicate that shorter initial delay is crucial for user retention, but some initial delay is preferred over any re-buffering event.

  Recently, a growing number of users prefer browsing through multiple videos before deciding to watch a particular video. Also, many platforms support the auto-play option, so the playback starts without any user intervention. In both the case, a low initial delay is essential and can be achieved either by pre-loading the few initial segments or by using higher throughput at the beginning of the playback.

- *Stalling*

  Stalling or Re-buffering is the event where the buffer does not have sufficient data to support playback. In other words, when the rate of consumption (player bitrate) is higher than the rate of loading (throughput), the buffer will eventually starve. Similar to the initial delay, the playback decision involves a trade-off between either resuming playback (reduce stalling duration) or replenishing buffer level (reduce stalling frequency). Both *stalling frequency* and *stalling duration* are considered as influential to the overall QoE [57]. Also, users tend to prefer experiencing a longer stalling over multiple shorted ones [58].

- *Adaptation/Quality Switching*

  As discussed previously, the goal of adaptation is to provide the best possible representation to the user. However, high *switching frequency* can be deteriorating for the user [59]. Moreover, the *amplitude* and *direction* of switching are also considered to be influencing the users QoE. When down-switching, smaller amplitude switches are considered better than a sudden high amplitude drop in representation [60]. Some models [61] also consider the *time spent on the highest layer* as a measure of QoE.

- *Video Quality*

  The quality of original media content is also highly influential to the overall QoE. Raw content due to its large size is encoded and compressed such that the resulting reconstruction is not noticeable by the human sensory system. Bitrate is the rate at which information is coded and decoded. Higher bitrate output (e.g. HD, UHD) is considered better over lower bitrate output (e.g. SD) for QoE [62]. The quantisation parameter (QP) used for encoding also affects the final QoE [63].

- *Multiple Clients*

  Having multiple clients in a network can greatly influence the overall QoE of the service. As shown in [64], a client joining first may occupy greater bandwidth which causes consecutive clients to switch to a lower bitrate. These clients suffer greater instability if network bandwidth allocation is not fair. This unfairness grows as more clients join the network. Moreover, if the clients use a conservative switching algorithm, this may lead to poor network utilisation [5]. These factors (*fairness* and *utilisation*) are of prime importance to network designers as the number of streaming clients across networks is growing.

### 2.4.2 QoE Measurement and Modelling

The measurement of a users QoE is crucial for understanding the performance of a streaming service or application. In essence, QoE is a subjective measure and is best measured using actual user feedback and test. The Mean Opinion Score (MOS) is the most suitable metric used in QoE tests. It is an average of the individual opinion scores of users and indicates the overall satisfaction with the service among its users. MOS is a numeric value ranging between 1 (meaning "Bad") and 5 (meaning "Excellent") in growing order of satisfaction. The ITU presents its guidelines for subjective tests in its recommendation specification ITU-Radiocommunication Sector (ITU-R) Rec BT.500 [65] and ITU-T Rec P.910 [54]. Subjective test results are often regarded as the gold standard for QoE analysis, and some datasets [66] are publicly available for quality assessment studies.

Despite being reflective of actual QoE, subjective tests are often expensive, resource-intensive and not always feasible. Thus, many systems use objective metrics for expressing the QoE of the users. These metrics are usually expressed by considering a subset of the influence factors (discussed in 2.4.1). An algorithm that uses these objective metrics to estimate the subjective QoE is called a QoE Model. Figure 2.13 describes a QoE management process, where an optimisation and control unit uses inputs from both measurement and modelling units to improve the systems overall QoE.

The choice of IF for measurement and modelling depends on factors like

- The stakeholders (e.g. network provider, service provider, device manufacturer or end-user) performing the study
- The IF of interest to the stakeholders
- Availability of reference signals (full-reference, reduced-reference or no-reference)

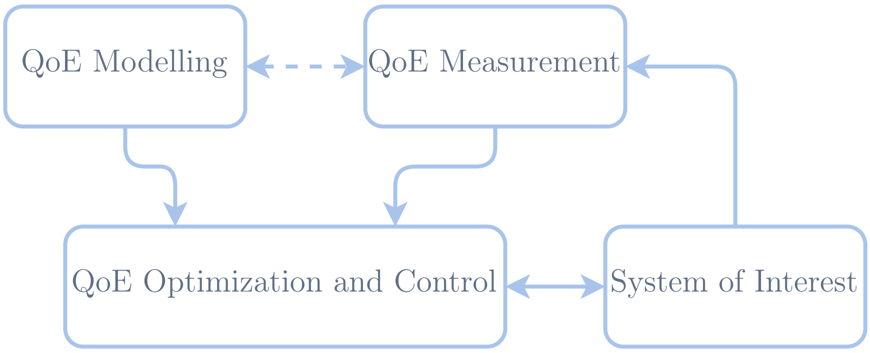



Figure 2.13: QoE Management System

- The nature of the application (e.g. audio, video, progressive streaming, adaptive streaming) being considered

QoE modelling is ongoing research, and many models have been developed over the past few years. A detailed discussion of these models here is beyond the scope and the interested reader is referred to [63], [5] and [67] for more details. For our purposes, we describe a model developed by Mok et al. [68] which gives an empirical expression for predicted MOS as given by (1).

$$MOS = 4.23 - 0.0672L_{ti} - 0.742L_{fr} - 0.106L_{tr} \tag{1}$$

where $L_{ti}$, $L_{fr}$ and $L_{tr}$ are the discrete levels of *initial delay*, *re-buffering frequency* and *re-buffering duration* respectively. The categorisation limits for these values are mentioned in Table 2.1. Their tests were performed on progressive streams using the Flash player.

| Level | Level Value | Initial Delay | Stalling Frequency | Total Stalling Time |
|---|---|---|---|---|
| Low | 1 | 0-1 seconds | 0-0.02 | 0-5 seconds |
| Medium | 2 | 1 -5 seconds | 0.02 -0.15 | 5 -10 seconds |
| High | 3 | $>$ 5 seconds | $>$ 0.15 | $>$ 10 seconds |

Table 2.1: Influence factor levels for MOS calculation

The resultant model was developed by measuring objective network and application QoS metrics and performing subjective tests to obtain a correlation between them. One of the advantages of the model is the absence of the reference signal, making it suitable for applications with encrypted traffic and network applications.

## 2.5 Related Work

Considerable studies have been undertaken to analyse video streaming performance. Some studies, e.g. [53][69][70], measure QoE and analyse the client player performances.

Though the results from these studies help identify critical influence factors for QoE, we focus on studies that analyse QoE from the perspective of network conditions.

### 2.5.1 LTE Networks

Zheng et al. [71] demonstrated the simulation of video streaming over LTE using a software emulator. Fouda et al. [72] measured throughput for video streaming clients in an LTE network. A similar analysis for Real-Time Messaging Protocol (RTMP) and Real-Time Streaming Protocols (RTSP) can be found in [73]. These studies are based on non-HTTP protocols, which limits their advantage for analysis of a large number of HAS solutions.

Aloman et al. [74] used a hardware-based network emulator to compare performance of DASH, RTMP and RTSP in LTE. Their measurements were performed on a single client, thereby lacking the effect of user location and interference models. Moreover, adding additional clients to an emulated setup requires additional networking configurations. Single client simulations have a disadvantage in that they fail to address the issues linked with the multi-client environment (see 2.4.1).

Chaari et al. [75] performed software-based LTE simulations with up to 20 clients. They measured the network QoS metrics, i.e. end-to-end packet delay and packet loss against different video categories and the number of users. The protocol used is, however, not mentioned, besides the QoE metrics have not been analysed. Guo et al. [76] proposed an LTE network optimisation using simultaneous transmission over unicast and multicast mode. They analyse the QoE of DASH streaming by measuring playback stability, resource consumption and video efficiency using Peak Signal-to-Noise Ratio (PSNR).

### 2.5.2 LWA Networks

A packet scheduling algorithm over LTE and WiFi channels is proposed by Park [77] using packed arrival timing from both channels at the receiver. An optimisation algorithm then distributes packets by solving a convex optimisation problem. Tests are conducted for up to 20 LTE and 8 WiFi users, indicate channel feedback from the UE can effectively help improve LWA network performance. Similar, traffic steering algorithm for live video traffic over RTP is proposed by Patidar et al. [78], where maximum channel capacity over both channels is estimated. Both approaches do not consider the end-to-end QoE, instead focus on network throughput. Basaras et al. [79] suggest splitting traffic over LTE-multicast channel along with WiFi unicast in LWA. An optimised algorithm for group allocation, bandwidth management and encoding rate for each group is provided. Their simulation results achieve significant improvements in video utility and resource allocation in LTE network.

As it is evident from the above studies, there is growing interest in the research community over network optimisations in LWA networks. The lack of open-source implementations is emphasised by the fact that only Chaari et al. [75] have made their source code open. In our study, we also try to address this gap and present an open-source simulation setup that can stream DASH content over multiple clients in both LTE and LWA networks.

# 3 Simulator Implementation

## 3.1 Network Simulator-3 (ns-3)

ns-3 is a software simulation framework that allows for large distributed simulation of networks. ns-3 is publicly available under the GNU GPLv2 license which allows for its modification and reuse. ns-3 is widely used for research and educational purposes and has extensive community support.

ns-3 primarily uses C++ programming language for development with support for Python using a special module *pybindgen*. ns-3 uses waf for its build automation and is supported on Eclipse IDE. Although, ns-3 supports both Linux and Windows (with Cygwin and Linux Subsystem for Windows) Operating Systems (OS), we use Linux as our development OS. It follows modular architecture wherein each module can be modified independently based on the task in hand. This flexibility also allows building and using custom modules.

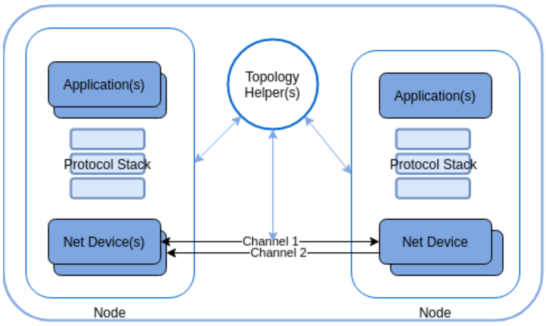


Figure 3.1: ns-3 key abstractions

Basic abstractions for ns-3 simulator include node, net device, application, channel and topology helper. A node represents any real-world device which can be configured for performing certain tasks. These tasks are part of applications. For communication between two applications on different nodes, net devices allow the flow of information over the channel. A channel connects multiple net devices and has certain properties depending on its configuration, e.g. P2P, LTE. Topology helpers implement common tasks (usually the ones that simulations would not change, e.g. assigning IP addresses) involving nodes, net devices and channels.

## 3.2 Implementing LTE

The development of *lte* module in ns-3 was undertaken under the LTE-EPC Network Simulator (LENA) Project [6], to evaluate radio-level performance and end-to-end QoE of the simulated systems. The *lte* module provides an implementation of various LTE and EPC entities, interfaces, propagation models and protocols. Performance of the *lte* module has been verified by Marinescu et al. [80] against 3GPP reference scenarios.

An overview of the model is depicted in 3.2. Overall end-to-end IP connectivity is provided between UE and remote-host devices using a combination of point-to-point, radio and logical links. The LTE model implements radio protocols (RRC, PDCP, RLC, MAC, PHY) within UE and EPC nodes. In contrast, the EPC model handles core networking entities, interfaces and protocols over eNB, MME, SGW and PGW nodes. Note that the models have been simplified considering the trade-off between complexity and scalability. An example of this simplification is that the SGW and PGW implementation has been added to a single node. Similarly, the PDCP model has limited implemented functionality; for example, it does not implement in-sequence delivery of upper layer PDUs and timer-based discarding. This functionality becomes crucial to the implementation of LWA, as will be discussed later.

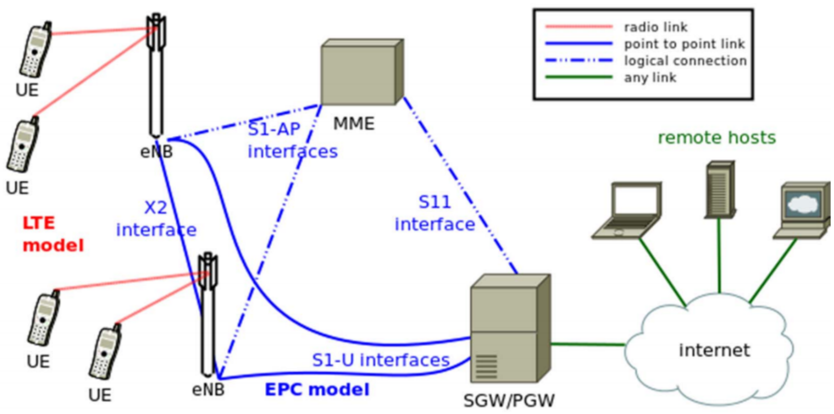



Figure 3.2: *lte* model overview [6]

The *lte* module provide two primary helpers, `LteHelper` and `EpcHelper` to expose various LTE and EPC functionalities. `EpcHelper` provides functions for assigning IPv4 network address and handling PGW and MME nodes. Whereas, `LteHelper` handles configurations related to radio channel like path-loss, fading, UE positioning and mobility, eNB bandwidth and bearer configurations. Other functionalities relating to creation of nodes, networking, tracing are provided by other ns-3 modules (*core*, *network*, *mobility*, *config* and *internet*).

## 3.3 Implementing DASH

### 3.3.1 Emulation

As seen in Section 2.5, some studies involve the use of emulated setup for DASH analysis. In an emulation setup, the network is simulated; however, some nodes are configured to use external services. ns-3 supports emulation scenarios using the *tap-bridge* module. We implemented an emulation scenario using Linux containers and bridged these container networks to the UE and remote host in ns-3 simulation. Two containers acting in a client-server configuration were created. DASH video was streamed using an apache2 HTTP server connected to the remote host. Whereas, a VLC instance as a DASH client was set up in the container connected to the UE. The display port of the container was connected to the host using a Unix socket (X11). Figure 3.3 shows a snapshot of the running simulation.

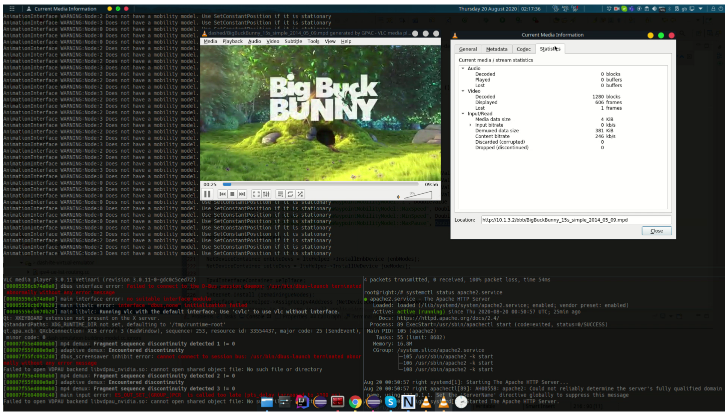



Figure 3.3: DASH emulation runtime snapshot: Console window to bottom-left running the VLC client, window to bottom-right running an apache2 server.

The advantage of using emulation is evident from the use of an external client. Besides making the implementation simpler, an external client can provide decoder statistics like lost audio, video frames and Full Reference metrics like PSNR and SSIM for Video Quality Assessment (VQA). These metrics are designed for quality analyses of compression and encoding techniques. However, there are some disadvantages to this approach:

- The scalability of the setup is a concern for resource-constrained hosts
- Full-Reference metrics like PSNR and SSIM are not always reflective of the actual QoE [63].
- QoE optimisations cannot be performed at the client based on FR metrics due to the lack of a reference signal.

Considering these factors, an entirely simulated DASH setup was implemented for our analysis.

### 3.3.2 QoE Model

Many network studies consider analysing solutions related to resource allocation, caching, traffic re-distribution (load-balancing). For these purposes, Packet-layer models for estimation of QoE are considered to be more useful. Packet-layer models like the one developed by Mok et al. [68] and discussed in Section 2.4.2, rely solely on information from packet (HTTP) timings and headers, rather than the actual signal. Thus, the simulated client should be able to measure received bitrate, packet loss, delay, playback details like initial delay, re-buffering events and segment variations. Moreover, sending virtualised/-dummy traffic data from the server (size corresponding to the requested representation by the client and MPD file) would suffice our purpose. This design choice also makes the simulation computationally inexpensive for large-scale network simulations

### 3.3.3 Simulation

Simulation setup requires DASH client and server applications to be implemented in NS-3. The AMuSt framework developed by Kreuzberger et al. [81] provides DASH client and server applications for ns-3. Moreover, it provides DASH playback traces using libdash [82], an official reference software of ISO/IEC MPEG-DASH standard. However, implementation was modified to create an independent module named *AMuSt* in ns-3 for better portability.

#### Client Application

The client application consists of a multimedia player which fetches segments based on adaptation logic. The client has configurable attributes like screen width, height, buffer duration, adaptation logic (e.g. rate-based, buffer-based), start time and stop time for each client. The simulator implementation sets random values for these parameters during runtime. DASH tracers can be installed on the clients to print out playback information as shown in Figure 3.4.

| Time | Node | UserId | SegmentNumber | SegmentRepID | SegmentExperiencedBitrate(bit/s) | BufferLevel(s) | StallingTime(msec) | SegmentDepIds |
|---|---|---|---|---|---|---|---|---|
| 5.618 | 21 | 0 | 0 | 1 | 75789 | 2 | 5515 | |
| 7.618 | 21 | 0 | 1 | 1 | 217872 | 4 | 0 | |
| 9.618 | 21 | 0 | 2 | 3 | 697308 | 4 | 0 | |
| 11.618 | 21 | 0 | 3 | 9 | 1236202 | 4 | 0 | |
| 13.618 | 21 | 0 | 4 | 12 | 784068 | 4 | 0 | |

Figure 3.4: DASH Client Trace: Statistics for first five segments

### Server Application

Server application similar to an HTTP server application in ns-3, manages client socket connections. On initialisation, it creates dummy segment data and stores in a temporary location for serving. Each connection from the clients, first includes a request for MPD file, followed by segment requests and tear-down. Figure 3.5 is taken from a simulation run with 4 UE requesting DASH video from a single server.

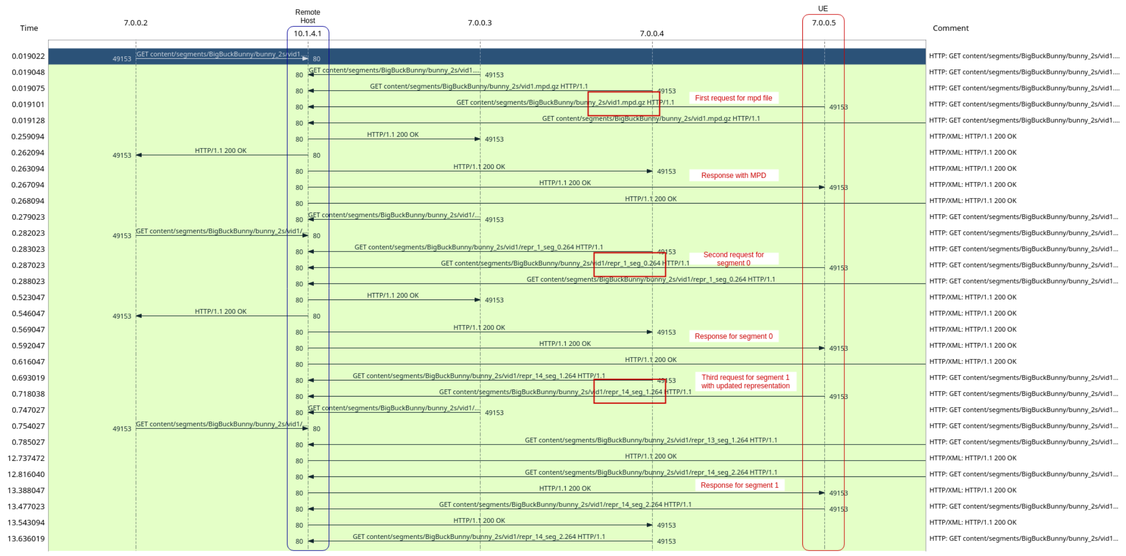
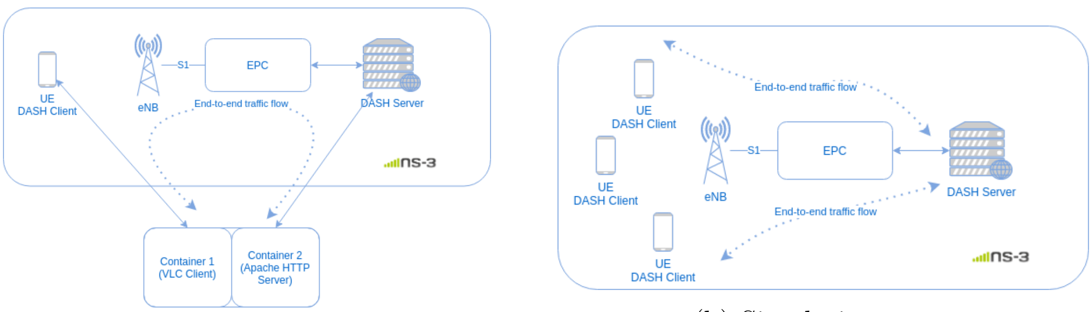



Figure 3.5: Wireshark flow for DASH segments:
Single host (10.1.4.1) serving multiple UEs. Highlighted flow for UE (7.0.0.5), shows MPD and segment requests

Both simulation and emulation setup are depicted in Figure 3.6.




(a) Emulation setup

(b) Simulation setup

Figure 3.6: LTE DASH Implementation

## 3.4 Implementing LWA

### 3.4.1 State of the art

Simulation of LWA networks in ns-3 has been previously studied [77][78][83]. However, the implementations by Park [77] and Patidar et al. [78] have not been made open, hence could not be extended for our study. A detailed description of LWA (non-collocated) implementation in ns-3 has been provided by Afaqui et al. [83]. They demonstrate the transfer of UDP traffic between remote client and UE. However, the implementation lacks PDCP layer aggregation (as suggested by 3GPP specifications) and support for in-sequence delivery (required for TCP and HTTP). To the best of our knowledge, there doesn't exist any implementation for PDCP aggregation and re-ordering for in-sequence delivery to upper layers.

### 3.4.2 Implementation

#### PDCP Transmission

The transmission logic at eNB was modified to support LWA operation. Following are some of the major modifications to the existing implementation:

- A new LWAAP header was defined containing bearer ID for identification of PDCP packets.
- The PDCP layer is connected to runtime simulation setup using ns-3 tracing mechanism. It allows passing information (PDCP PDU in this case) from *lte* module to the actual simulator implementation. A handler is attached to the trace for processing these PDUs and forwarding to WT.*
- Because `pdcp-lte.cc` is a common implementation for eNB and UE, a new field `isUe` was added to the PDCP layer and set by the `lte-ue-rrc.cc` and `lte-enb-rrc.cc` to true and false respectively.
- A UDP socket connecting to each UE connections was created for transmission over WiFi. Each socket is mapped to respective UE's Radio Network Temporary Identifier (RNTI). RNTI from incoming packets in handler are retrieved and corresponding socket is selected for sending data.

Figure 3.7 shows flowchart for PDCP transmission.

*This approach was first implemented by Afaqui et al. [83]

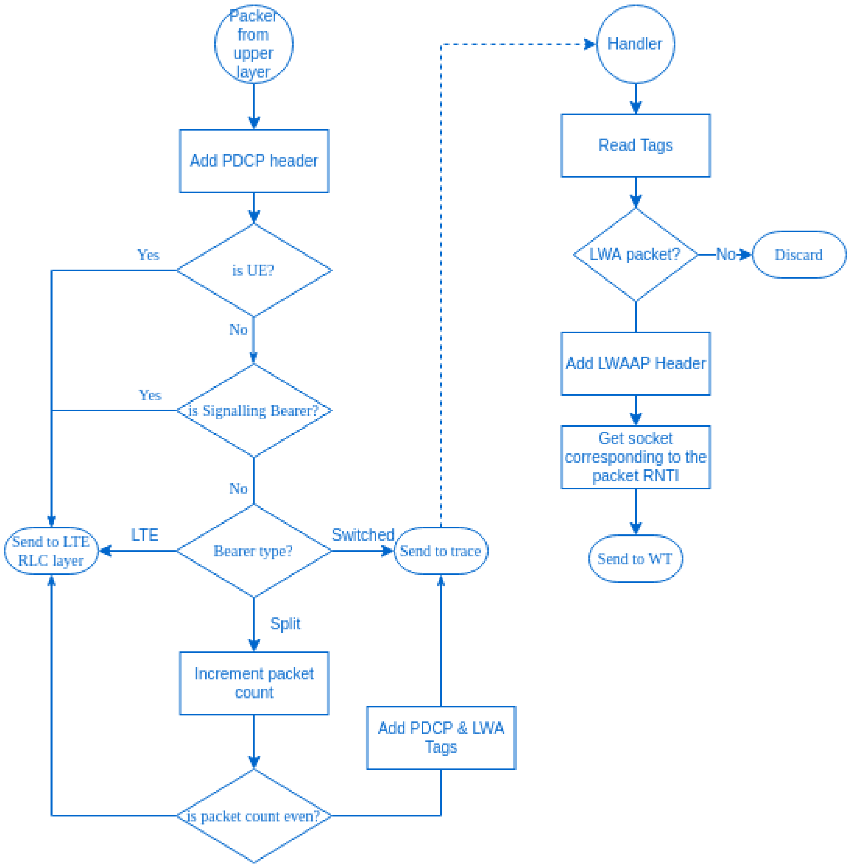



Figure 3.7: Flowchart for PDCP transmission

### PDCP Reception

For reception logic was modified at UE to support aggregation of packets. Following are some of the modifications to the existing implementations:

- A socket is connected to the PDCP layer of each UE for receiving incoming packets over WiFi. The socket is attached by `lte-ue-rrc.cc` every time a DRB is created.
- A callback attached to the socket removes the LWAAP header and forwards the PDCP SDU for aggregation. Note that each packet needs to be associated with corresponding DRB, however, in current scenario each UE has only a single DRB connection hence this mapping had not been implemented.
- A packet reordering algorithm was implemented according to 3GPP TS 36.323 PDCP specifications [29]. A reordering timer and a storage buffer was added at PDCP layer.

Figure 3.8 shows flowchart for PDCP reception.

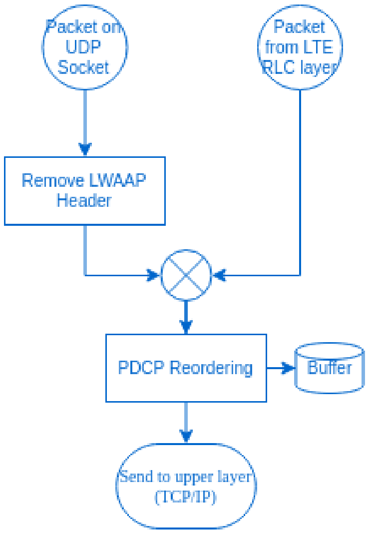



Figure 3.8: Flowchart for PDCP reception

### Limitations

The current implementation handles re-ordering of packets at PDCP, which allows for the UE to accept WiFi traffic and deliver packets to upper layer applications. Other LWA functionalities, apart from reordering, such as LWA status reporting, switching of bearers, monitoring of WLAN metrics have not been implemented due to the limited scope of our study. The source code for the implementation is made available for verification and modification [84].

# 4 Evaluation

This chapter describes the tests performed using the implemented simulator. In the first section, we perform QoE analysis of DASH in an LTE deployment. We evaluate the QoE using two different scenarios, i.e. using 3GPP reference parameters and varying UE density and DASH segment duration. In the second section, LWA implementation has been analysed for video streaming.

## 4.1 LTE Evaluation

### 4.1.1 3GPP Reference Scenario

The RAN configurations for LTE simulation are based on 3GPP TR 36.814 [85] and TR 25.814 [86] simulation scenarios. More specifically we implement the urban macro deployment i.e. case 1. A cellular layout of 19 cell sites each with three sectors was implemented and UE density of 25 UEs per cell site were uniformly located. The simulation was performed for a period of 10s, with DASH segment duration of 2s. The radio environment for the setup is shown in Figure 4.1. Other values for the LTE and DASH simulation parameters are provided in Appendix Table A1.1 and Table A1.2 respectively.

The simulation consisted of 1425 UEs in total and DASH tracers were installed on each of the device. We measured the average bitrate, initial delay and re-buffering data. Figure 4.2a shows the categories of initial delay and stalling time according to Table 2.1. The results show that 84% users experience moderate delay (1s-5s) with a mean delay of 3.8 seconds. On the other hand, 98.7% users experience no stalling. Using the equation 1, we calculate the MOS values for all users. Figure 4.2b shows the spread of MOS values with its median value being 3.25 which maps to an *average* experience.

### 4.1.2 Changing UE density and DASH segment duration

The QoE performance was further analysed by repeating the simulation for different UE densities and DASH segment duration. Two major influence factors start-up delay and

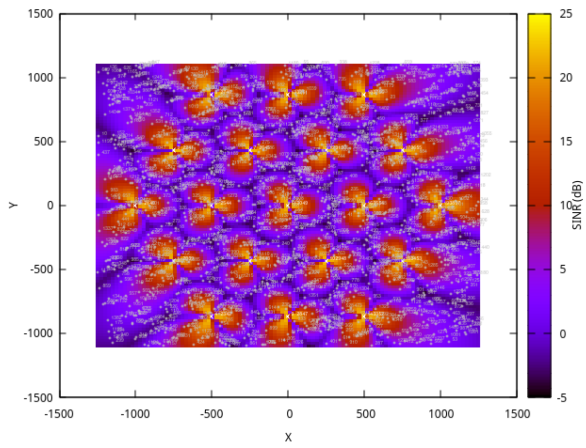



Figure 4.1: Radio Environment Map for LTE Simulation: 19 cell sites with 3 sectors per site. 25 UE per cell site, distributed uniformly


(a) Initial Delay and Stalling Time

(b) MOS. Minimum: 1.55 and Median: 3.25

Figure 4.2: Initial Delay and Stalling in 3GPP reference scenario and Overall MOS

stalling are plotted in Figure 4.3 in terms of percentage of users. Using percentages rather than mean values for start-up time and stalling provides better representation of individual user's experience. It is observed that by using 2s segments, lower startup delay is experienced by users. However, proportion of users experiencing stalling is higher for 2s segments. Since, stalling has a higher impact on QoE as compared to initial delay, segment duration longer than 2s can be considered.

The drop in average download rate can be observed when the UE density increases. Figure 4.3c shows that the download rate drops for both segment duration. A larger variation is observed for 15s segments. Another factor determining the QoE is the quality variation. Quality variations are low for 15s duration, and increase with user density irrespective of segment duration. When 2s segments are used, the buffer level has a median value of 1s and maximum of 6s of buffer availability. This value is considerably higher than 15s segments, which have a median of 0s. The plots for quality variation and buffer level are provided in Figure 4.3. Considering 2s and 15s segment duration are often extreme values, based on the type of service and desired influence factors of interest, appropriate segment duration can be selected.

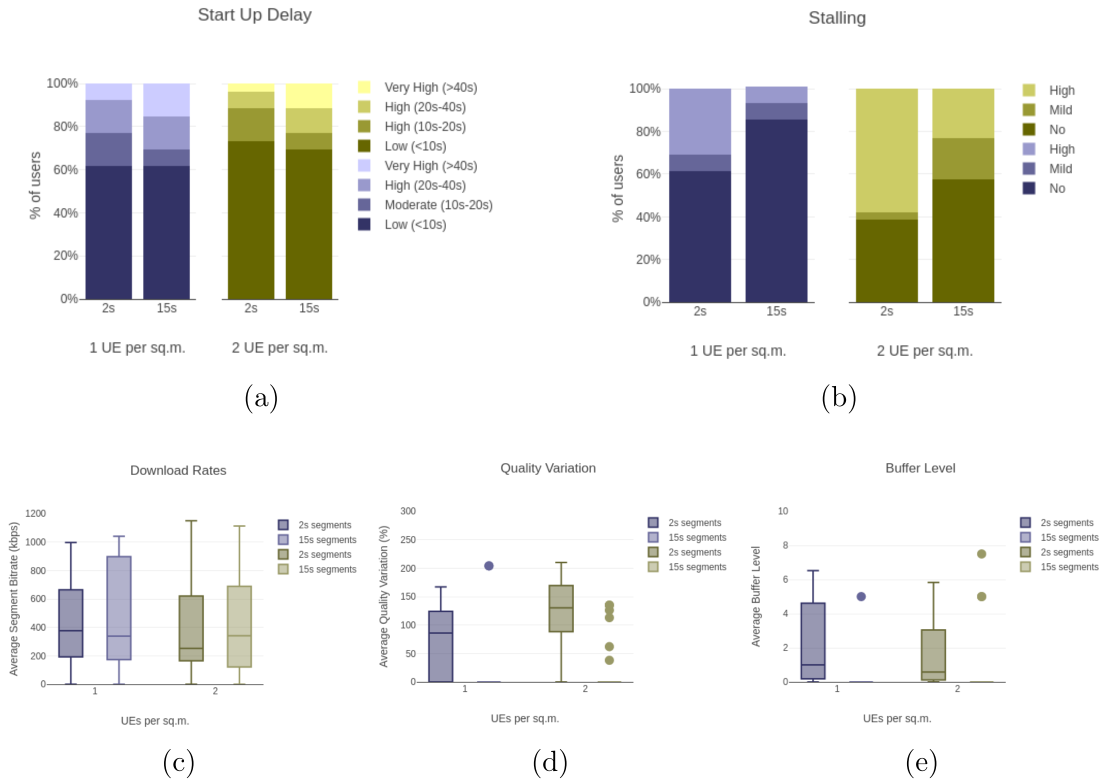



Figure 4.3: Influence factors for different UE density and DASH segment duration values

## 4.2 LWA Evaluation

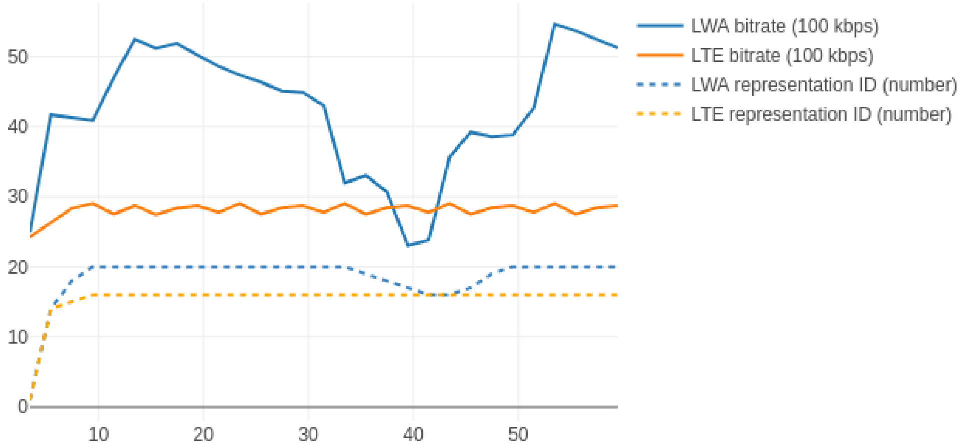
Due to the limitations of the LWA implementation, it is only possible to support either LWA or LTE bearers at a time and only a single AP node is used, this limits the number of devices in LWA.

### 4.2.1 Changing the number of UE

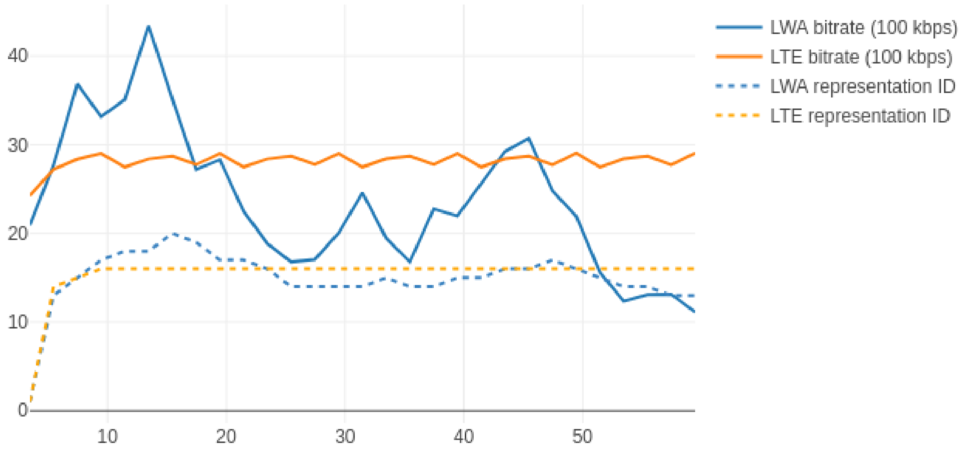
In this simulation, each UE is connected to a WiFi AP and LTE eNB. In LTE mode, eNB sends all data through RLC and LTE radio channel and no data is sent over WiFi. In LWA mode, eNB splits packets in 1:1 ratio such that half of the transmissions are over WiFi. The implemented PDCP re-ordering is active in both the modes.

We run three scenarios with 2, 4 and 8 UE acting as DASH clients. We plot the segment bitrate and player selected representation (1-lowest, 20-highest) for the segment, against the playback time. It is observed that high bitrate is achieved but is unstable, which causes high quality variations, for e.g. in Figure 4.4a, the representation drops from 20 to 15 within a time frame of 6 seconds. Furthermore, as the number of UE connected to WiFi AP increase, a drop in bitrate is observed. Bitrate in LTE mode, on the other hand, remains constant.

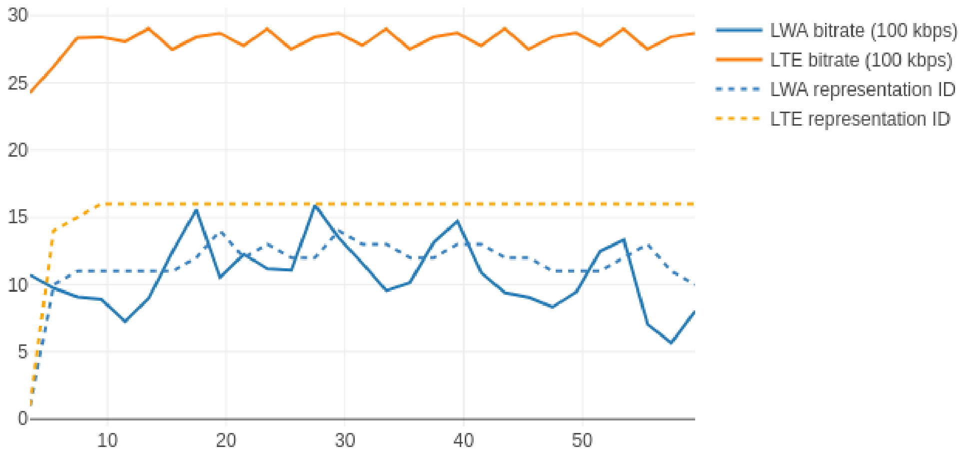
Using longer segment duration helps avoid these sudden representation changes. This




(a) Number of UE = 2



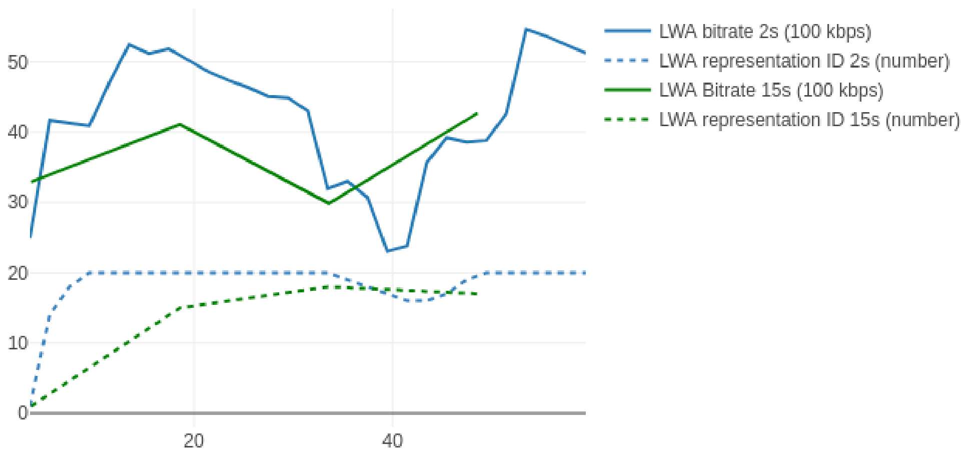

(b) Number of UE = 4



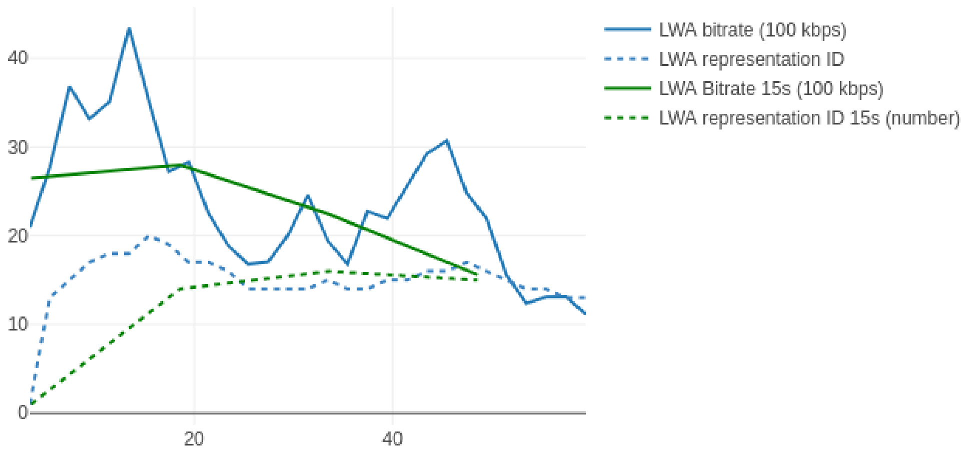

(c) Number of UE = 8

Figure 4.4: LWA and LTE bitrate and representation for 2s segments: LWA bitrate drops as number of UE increases

stabilisation is evident from plots in Figure 4.5. The client receives lower representation initially, but less quality variations especially no sudden drops. Moreover, when there is a continuous drop in received throughput, longer segment allows for eNB to switch bearers based on UE or WLAN measurements.




(a) Number of UE = 2




(b) Number of UE = 4

Figure 4.5: LWA bitrate and representation for 15s and 2s segments: 15s segments allow for low variations at the cost of low initial quality

# 5 Conclusion

In this study, we analysed the Quality of Experience of users streaming video over a cellular link. A thorough study of different influence factors, QoE models and metrics was conducted. A widely-used open-source simulator, ns-3, has been used for implementing DASH over an LTE network. The feasibility of the approach was successfully verified by implementing 3GPP standard scenarios including handover, fading and mobility.

Furthermore, considering the rising focus on LTE operation in Unlicensed spectrum, different approaches like LAA and LWA were studied. The lack of sufficient functionality to simulate LWA was addressed by modifying the *lte* module in ns-3. Finally, a DASH video was streamed over the LWA network, and performance improvements were analysed.

Overall contributions of this study can be summarised as below:

- Presenting an open-source implementation of the existing state of the art for video streaming in LTE. This study will save network designers the effort of implementing DASH clients and servers, thereby focusing on the network aspects. Moreover, since both emulation and simulation approaches have been implemented, the setup is useful for real hardware integration.
- Some of the existing modules for DASH simulation in ns-3 have been archived, e.g. [81] and required modifications before using. Our implementation is based on the latest ns-3 version (version 31) and updated modules.
- The *lte* module does not implement aggregation at the PDCP layer of LTE. Our implementation addresses this missing functionality, thereby allowing simulations involving PDCP aggregation.

## 5.1 Future Work

Current simulator implementation has a wide scope of improvement, modification and re-use. Some of the possible works that can be undertaken in future are as follows:

- Despite the implemented re-ordering functionality at the PDCP layer, LWA implementation involves other functions like status reporting, WLAN handover, measurement and reporting of WLAN metrics and switching of bearers. Moreover, the current raw socket implementations can be migrated into the LTE stack for better design of the system, thereby avoiding tedious mappings of sockets to UE bearers.
- A hybrid LTE multicast and WiFi unicast aggregation as suggested by Basaras et al. [79] can be implemented. Currently, the EPC architecture does not implement Multimedia Broadcast Multicast Services (MBMS), and hence additional work is required in this area.
- The PDCP re-ordering implementation can be re-used or adapted for other aggregation technologies like LTE-DC, i.e. Home eNB (HeNB) and Secondary eNB (SeNB) aggregation, and LTE-NR, i.e. aggregation of LTE and New Radio (NR) RATs.

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# A1 Appendix

## A1.1 Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Simulation Time | 10s (3GPP Scenario)<br>60s (All other scenarios) |
| Cellular Layout | 19 cell sites, 3 sectors per site |
| Antenna Height | 32 m |
| Antenna Beamwidth | 70 |
| Maximum Attenuation | 25 dB |
| Cell Tx Power | 46 dBm |
| UE Power Class | 25 dBm |
| Pathloss Model | $128.1 + 37.6log_{10}R$, where R dist in km |
| UE height | 1.5m |
| Carrier Frequency | 2 GHz |
| UE speed | 3 km/h |
| Downlink Scheduler | Round Robin |
| Transmission Type | 1x2 SIMO FDD |
| Bandwidth | 20 MHz (10 MHz downlink/10 MHz uplink) |
| Distance between cells | 500 m |
| UE distribution | 25 uniformly distributed UEs per cell (3GPP Scenario) |
| Antenna downtilt | 15 |

Table A1.1: LTE Baseline Parameters

| **Parameter** | **Value** |
|---|---|
| Segment Duration | 2 sec and 15 sec |
| Adaptation Algorithm | Rate-Based Adaptation |
| Frames per second | 24fps |
| Video sample | Big Buck Bunny |
| Resolution | 320×240<br>480×360<br>854×480<br>1280×720<br>1920×1080 |
| Bitrate | 45kbps - 3.7 Mbps |

Table A1.2: DASH Parameters