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5G Broadcast for Mobile Video Streaming

Tesi di Laurea Magistrale in Computer Science and Engineering - Ingegneria Informatica

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All the Beauty
and the Bloodshed

Abstract

The rapid evolution of communication technologies has brought forth a dynamic landscape for digital media platforms. Smartphones, tablets, Virtual Reality (VR) devices, and Augmented Reality (AR) glasses have seamlessly integrated with TVs, creating a multimedia communication paradigm. In this context, media companies are turning to 5G technology for revolutionary content delivery possibilities.

This thesis aligns with the ministerial project *"Rai Way Experimentation of 5G Broadcast Network and Services in the 700 MHz Band in the Cities of Turin and Palermo"*, a collaborative effort led by RaiWay and involves key partners such as RAI Research, Politecnico di Milano, Rohde&Schwarz, MainStreaming, Impersive, and Kineton. Its objectives include implementing 5G Broadcast according to 3GPP Rel.14, showcasing tailored utilization scenarios, integrating advanced technologies like Content Delivery Network (CDN) and VR360° production, and testing the technology using granted transmitters in Turin and Palermo.

The thesis dives into the integration of 5G Broadcast and CDN technologies, emphasizing the development of a Seamless Switching Application (SSA) to ensure uninterrupted service delivery. It explores practical tests, with a particular emphasis on the automotive use case, in pursuit of fine-tuning SSA parameters and enhancing its effectiveness.

The research findings contribute to the evolving landscape of media delivery, with a focus on live event transmission, enabling seamless, high-quality content distribution to a growing audience, with applications extending beyond entertainment.

Keywords: Audiovisual content, 5G Broadcast, Content Delivery Network (CDN).

Abstract in lingua italiana

L'evoluzione rapida delle tecnologie di comunicazione ha portato a un panorama dinamico per le piattaforme di media digitali. Smartphone, tablet, dispositivi di Realtà Virtuale (VR) e occhiali di Realtà Aumentata (AR) si sono integrati con le TV, creando un paradigma di comunicazione multimediale. In questo contesto, le aziende di media stanno puntando sulla tecnologia 5G per rivoluzionare le possibilità di distribuzione dei contenuti.

Questa tesi è in linea con il progetto ministeriale *"Sperimentazione di Rai Way della Rete e dei Servizi di Trasmissione 5G nella Banda a 700 MHz nelle Città di Torino e Palermo"*, un sforzo collaborativo guidato da RaiWay che coinvolge partner chiave come RAI, Politecnico di Milano, Rohde&Schwarz, MainStreaming, Impersive e Kineton. Gli obiettivi includono l'implementazione di 5G Broadcast secondo le specifiche 3GPP Rel.14, la presentazione di casi d'uso personalizzati, l'integrazione di tecnologie avanzate come la Rete di Distribuzione dei Contenuti (CDN) e la produzione VR360°, e la verifica della tecnologia attraverso trasmettitori concessi a Torino e Palermo.

La tesi esamina l'integrazione delle tecnologie 5G Broadcast e CDN, ponendo l'accento sullo sviluppo di un'applicazione di Switching Continuo (SSA) per garantire la continuità del servizio. Questo lavoro esplora test pratici, con particolare attenzione al caso d'uso automobilistico, al fine di perfezionare i parametri dell'SSA e migliorarne l'efficacia.

Le scoperte della ricerca contribuiscono all'evoluzione del panorama della distribuzione dei media, con particolare attenzione alla trasmissione di eventi dal vivo, consentendo una distribuzione dei contenuti con continuità e di alta qualità a un pubblico sempre crescente, con applicazioni che vanno oltre l'intrattenimento.

Parole chiave: Contenuti audiovisivi, 5G Broadcast, Rete di Distribuzione dei Contenuti(CDN).

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1 | Introduction

Over the past few decades, the ever-evolving landscape of communication technologies has witnessed the emergence of new players within the highly competitive domain of digital media platforms. The widespread adoption of smartphones, tablets, laptops, Virtual Reality (VR) devices, Augmented Reality (AR) glasses, and other sophisticated endpoints capable of seamless interaction with TV sets in a "smart" manner has propelled the media industry towards a more integrated and multimedia communication approach. This evolution has paved the way for a wide array of value-added products and services, promising an enhanced and immersive user experience.

In the pursuit of offering an extensive range of services to a vast user base, media companies have turned their attention to the groundbreaking opportunities presented by 5G technology. The introduction of novel functionalities in the broadcast/multicast profile of 3GPP Rel-14/16 [1, 2], commonly known as "5G Broadcast", has the potential to revolutionize content delivery and confer a competitive advantage to all stakeholders in the media value chain: content and service providers, Mobile Network Operators (MNOs), manufacturers, and Broadcast Network Operators (BNOs).

The 5G Broadcast paradigm enables content and service providers to deliver free-to-air media services to mobile devices with guaranteed a high quality guarantee, irrespective of the number of concurrent viewers, without disrupting regular cellular 5G networks. This, in turn, helps mitigating Content Delivery Network (CDN) costs for popular live content. From the perspective of MNOs, 5G Broadcast offers the opportunity to optimize network resources by dynamically utilizing the more efficient broadcast mode for delivering linear/live video traffic to large audiences.

For manufacturers, the integration of 5G Broadcast functionalities in mobile terminals with limited hardware and firmware upgrades unlocks new commercial prospects and market opportunities. Furthermore, this technology holds promise for various consumer applications, particularly in the automotive sector, where safe and reliable communication systems are essential for vehicle-device connectivity, real-time traffic, and Vehicle-to-Everything (V2X) delivery. Moreover, 5G Broadcast facilitates efficient dissemination of public warning messages, such as urgent weather alerts and community information.

From an environmental standpoint, broadcast technology is lauded as the most sustainable and eco-friendly alternative for delivering linear TV content, boasting the lowest CO2 emissions. For instance, Digital Terrestrial Television (DTT) in Europe exhibits significantly lower impact compared to Over The Top (OTT) and managed Internet Protocol Television (IPTV) services [3].

The ongoing multitude of tests and trials conducted worldwide [4–6] serves as a testament to the promising potential of 5G Broadcast in meeting future content distribution needs. This technology has the capability to reshape the media landscape, providing seamless and high-quality content delivery to an ever-expanding audience.

In the following section, the project description will be presented (Sec. 1.1), with a focus on the distribution network architecture (Sec. 1.1.1), the system architecture (Sec. 1.1.2) and the use cases (Sec. 1.1.3).

Finally, the thesis structure and contributions (Sec.1.2) will be introduced.

1.1. Project description

This thesis is closely aligned with the implementation of a ministerial project where Politecnico di Milano is a partner [7].

Specifically, the project titled "Rai Way Experimentation of 5G Broadcast Network and Services in the 700 MHz Band in the Cities of Turin and Palermo" involves cooperation between several partners coordinated by RaiWay. The main ones include RAI Research, Technological Innovation and Experimentation Centre (CRITS), Politecnico di Milano, Rohde&Schwarz, MainStreaming who worked on the development of transmission and reception side technology; while Impersive and Kineton were interested in integrating this technology into the practical use of the services they offer.

The project objectives are as follows:

- Implementing a 5G Broadcast solution, as mandated by 3GPP Rel.14.
- Leveraging 5G Private Network technology at designated locations in Turin, such as Officine Grandi Riparazioni - OGR, to contribute produced media content.
- Presenting use cases in five specific areas, customized to suit the needs of the experimental territory.
- Integrating cutting-edge technologies, including CDN for media content processing

and distribution over the broadband channel, VR360° for immersive video production, 5G Broadcast technology for audiovisual content delivery to mobile devices, 5G Private Network technology, Local Edge CDN for content redistribution to connected users within the 5G Private Network coverage area, introduction of Qualcomm prototype devices for receiving 5G Broadcast content, and WiFi 6 technology for the final content delivery to terminals.

- Develop a series of use cases to test the technology, exploiting the transmitters granted for experimentation in the cities of Turin and Palermo.

Politecnico di Milano's involvement in the project focuses on developing Seamless Switching Application (SSA), a software for receiving 5G Broadcast and broadband audiovisual signals that enables cooperation between the two modes to maintain high streaming quality.

1.1.1. Distribution network architecture

The content distribution platform fully leverages the capabilities of the existing terrestrial transmission network infrastructure belonging to Rai Way, the broadcaster. It incorporates new functionalities developed in 3GPP Rel-14/16 [1, 2] to facilitate the broadcast-mode delivery of multimedia content to personal handheld devices.

The network setup is illustrated in Figure 1.1.

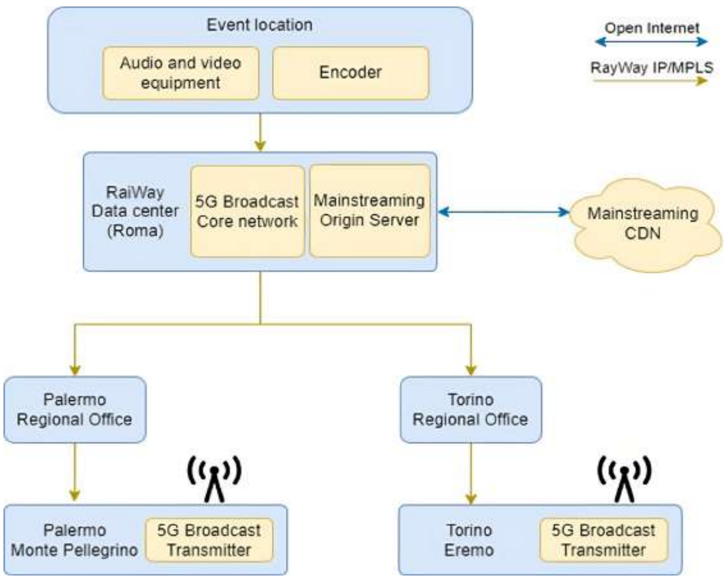


Figure 1.1: Network architecture of stream distribution [9]

The Rai Way transport network serves a dual purpose of contribution and distribution. Contribution involves exchanging programs between Rai regional offices and Production Centres in Rome, Milan, Turin, and Naples. Distribution pertains to transporting national and regional radio and TV programs, including Digital Terrestrial Television (DTT) and Digital Audio Broadcasting (DAB), to all broadcasting centers (over 2,000 sites). The network relies on optical fibers for long-distance connections and employs Internet Protocol (IP)/Multiprotocol Label Switching - Traffic Engineering (MPLS-TE) technology for the transport service.

In the context of the ministerial project, Rai Way's transport network handles both sending contribution video streams to the Rai Way Data Centre in Rome and delivering distribution streams to 5G Broadcast transmitting sites in Turin and Palermo. The core component of the 5G Broadcast Network in this project is the 5G Broadcast Service & Control Centre (BSCC) provided by Rohde & Schwarz. BSCC facilitates multimedia content delivery over 5G networks in broadcast mode, utilizing instances like Broadcast Multicast Service Centre (BM-SC) and Multimedia Broadcast Multicast Service Gateway (MBMS GW). Alongside live and linear content, the BSCC enables simultaneous delivery of various content types, such as file-based, Over-the-Air (OTA) updates, and public alerts. These capabilities are governed by protocols outlined in 3GPP standards, including File Delivery over Unidirectional Transport (FLUTE), Dynamic Adaptive Streaming over HTTP (DASH) and HTTP Live Streaming (HLS).

Collection, processing, and distribution of different types of live video streams has been provided by MainStreaming [8]. This process involves a MainStreaming StreamLive dedicated machine stationed at the Rai Way datacenter in Rome, handling source stream reception, transcoding and/or packaging, and distributing to both the BSCC server (for 5G Broadcast transmission) and the MainStreaming Global CDN caches (for broadband transmission).

For the Turin coverage area, the streams coming from the BSCC located in Rome are then forwarded on the Rai Way IP/MPLS-TE network to the Turin Regional Office and hence to Eremo Transmission Centre by means a direct fibre connection.

Similarly, for the Palermo coverage area, streams from the BSCC are sent to the Palermo Regional Office via a fiber connection and then transmitted to the Palermo M. Pellegrino Transmission Centre through a radio link.

1.1.2. System architecture

Figure 1.2 illustrates the block diagram of system architecture's designed by Rai Way for delivering content to mobile devices in the project, facilitating smooth transitions between 5G Broadcast and OTT unicast A/V streams.

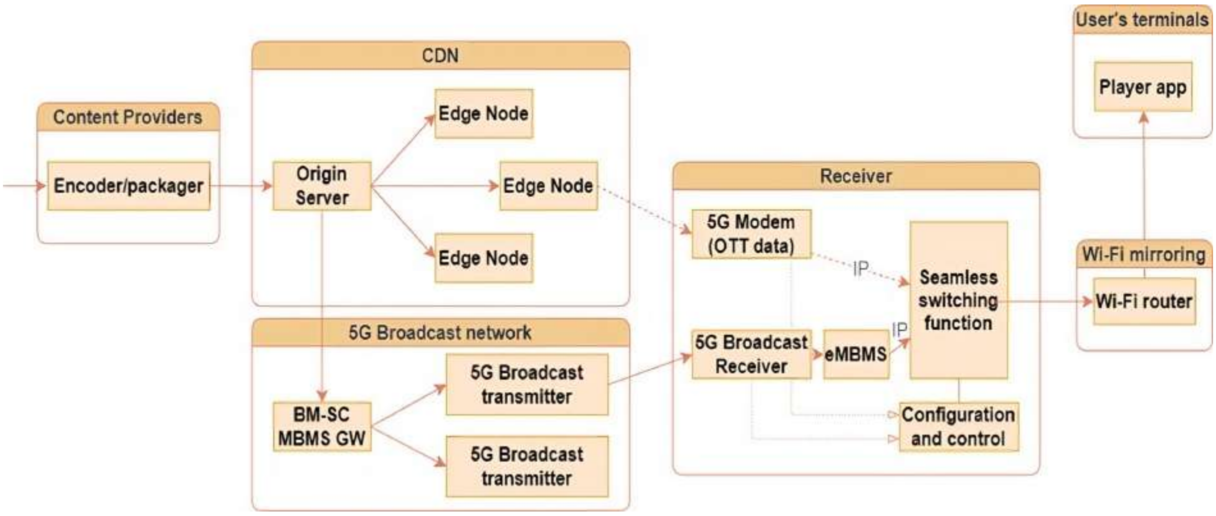


Figure 1.2: System architecture [9]

Key components necessary for achieving this objective within the content delivery process include:

- Implementation of Adaptive-BitRate (ABR) technologies like HLS or MPEG DASH, which allow the same encoded content to be delivered through both 5G Broadcast and OTT broadband. This approach capitalizes on CDN distribution.
- A dedicated receiver-side application capable of automatically switching to the broadband when signal impairments are detected in the 5G Broadcast signal. The application then reverts to the 5G Broadcast signal once it becomes available again. This process ensures proper synchronization of the two streams in terms of timing.

The encoder/packager employs HLS to publish audio/video streams supplied by content providers. These streams are made accessible to the MainStreaming Origin Server and CDN. The same HLS segments also feed the BM-SC and MBMS GW functionalities integrated into the Rohde & Schwarz BSCC. The BSCC encapsulates these segments into a FLUTE stream, ready for delivery via the nationwide Rai Way distribution network to the 5G Broadcast transmitters in Torino Eremo and Palermo Monte Pellegrino.

The receiver operates on a PC platform running the SSA developed by Politecnico di Milano.

Depending on the specific use cases, the audio/video content is consumed either on the vehicular infotainment system or on personal devices (such as smartphones, tablets, VR) connected via Wi-Fi to the receiver. An Android app created by Kinecar facilitates this connectivity. Further details regarding additional functions or variations within the system architecture, relevant to specific use cases, are expounded in the next section.

1.1.3. Use cases

The use cases implemented during the project, presented through various live events, were carefully designed to evaluate specific aspects of system performance. All the experiments were made feasible by covering the cities of Turin and Palermo with High Power High Tower (HPHT) transmitters operating in the 700 MHz frequency band for Supplemental Downlink (SDL). This frequency was made available by the Ministry of Infrastructure and Telecommunications for the duration of the project. These transmitters were integrated with CDN distribution, implementing a combination of hybrid 5G Broadcast and broadband services.

Live TV Distribution (LTVD)

In this scenario, live audio and video content, captured by wireless cameras and microphones connected through a 5G private network, is distributed to end-users via 5G Broadcast. The distribution is further enhanced by seamless switching with broadband connectivity. The primary challenge here is to minimize end-to-end latency, ensuring real-time delivery of content to users.

To achieve low latency, various aspects of the delivery chain are optimized, including:

- Fine-tuning of encoding and packaging profile parameters like Group of Pictures (GOP) and segment length. Implementing chunked transfer encoding (Low Latency DASH) offers further improvements.
- Efficient media ingest workflow reduces transfer latency to the Origin server.
- CDN configuration is optimized, particularly for viewers attending the live event. A dedicated local edge node of the CDN is installed on-site, connected to the same 5G private network used for remote TV production (Fig. 1.3).
- Efficient Broadcast Multicast Service Centre (BM-SC) feeding. This latter aspect requires pushing the A/V streams from the CDN to the BM-SC rather than pulling them, with inherent buffering. In turn, this requires that a CDN node has direct network visibility, i.e., without firewalls, with the BM-SC (e.g., co-located).

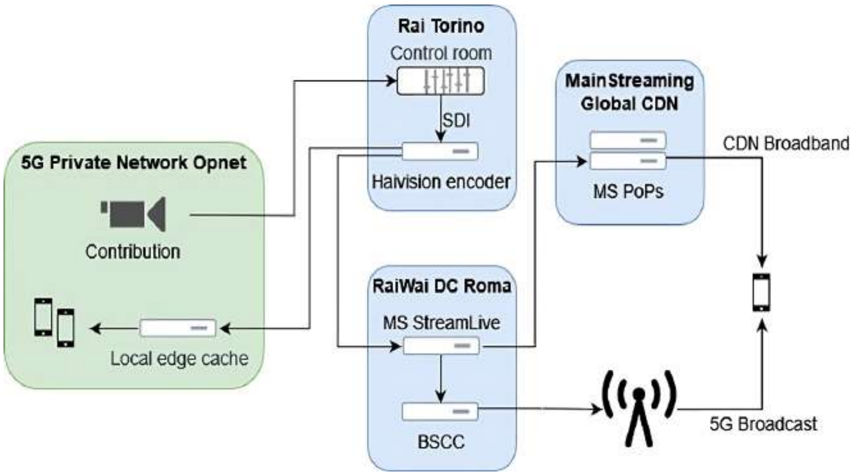


Figure 1.3: Integration of a local edge cache [9]

Auto Infotainment Content Consumption (AICC)

Kinecar (Fig. 1.4) is an electric microcar developed by Kineton that comes equipped with multiple communication interfaces facilitating information exchange both within the car and with the external environment [10]. It incorporates advanced smartphone-like features through an innovative "intelligent system" capable of gathering and processing data from various sources, including on-board sensors, radar, infrastructure, and more. This information is then made available to the driver and passengers through a flexible and adaptive Human Machine Interface (HMI).

Figure 1.4: Kinecar [10]

To achieve this, a dedicated Android app has been developed as part of the project. This app allows users to connect to the car's receiver and access HLS A/V services on the vehicle's infotainment system or on personal devices connected to it.

The primary challenge in this use case is ensuring robust reception while the car is in motion. Addressing this challenge required a meticulous evaluation of the receiving antenna's performance when mounted on the car. Additionally, improvements were made to the 5G Broadcast receiver's channel estimation and seamless switching function to enhance the overall reception experience.

VR360 Content Consumption (VRCC)

In this scenario, the objective is to distribute live immersive VR360 content captured during a ballet rehearsal. The event was produced at Teatro Massimo in Palermo using multiple stereoscopic VR360 cameras. Pre-recorded VR360 contributions were inserted, placing the narrator/actor at various points within the location to evoke emotions, enhance effectiveness, and engage the audience (Fig. 1.5).

The VR360 video streams, after being processed by the Impersive stitching and coding system, were transmitted via Rai Way contribution network from the theatre to the Mainstreaming Origin server located at the Rai Way Data Centre in Rome. From there, they were delivered to the 5G Broadcast network, as explained earlier.

Figure 1.5: VR Content Consumption [11]

During the event, designated areas within the theatre and a high school were set up for users to experience the content using a VR headset connected via WiFi-6 to the 5G Broadcast receiver. This allowed users to immerse themselves in the VR experience and actively participate in the action.

The main challenge in this use case is delivering high bit-rate streams. To provide a fully immersive experience, the encoding bit-rate needs to be sufficiently high. Preliminary laboratory tests indicate that for a VR360 video with 3840×3840 resolution and High Efficiency Video Coding (HEVC), an acceptable bit-rate is approximately 10 Mbit/s. This bit-rate is necessary to ensure a seamless and immersive VR experience for the users.

1.2. Thesis structure and contributions

The proposed thesis aims to explore some aspects of the Politecnico di Milano's contribution to the ministerial project described in the previous section.

The thesis opens with a comprehensive understanding of 5G receiver, obtained by studying the 5G transmission technology and video streaming protocols in Chapter 2.

A detailed overview of the receiver architecture is then presented in Chapter 3, as open source software provided by 5G-MAG was used as a starting point. 5G Media Action Group (5G-MAG) is a Swiss group that focuses on developing software for collaboration between the media and telecom industries, utilising 5G technology.

The core focus of the work is to establish efficient cooperation between broadcast and broadband networks, ensuring uninterrupted service for users in deep urban areas where coverage guaranteed by HPHT sites alone may be insufficient. This is achieved by implementing Seamless Switching Application (SSA) presented in Chapter 4, which aims to make the service as transparent as possible to the user.

The final chapter (Chapter 5) focuses on the automotive use case, conducting practical tests and exploring potential enhancements in the SSA's parameterization.

I have actively participated in the development of the SSA and played a significant role in resolving bugs in the 5G-MAG receiver to enhance its stability. Additionally, I have conducted an in-depth analysis of the data collected in Torino and have worked on improving the parameters of the SSA. My involvement in these aspects of the project has been instrumental in advancing our research and achieving our objectives.

Based on the topics covered in this thesis, *"Efficient delivery of audiovisual content to mobile devices combining 5G Broadcast and CDN technologies"* article was also published for IBC2023 [9].

Additionally, we were honored to be recognized as finalists for the European EBU Technology & Innovation Awards [12].

2 | 5G transmission technology and video streaming protocols

The 5G is the fifth generation of mobile network technology, offering high-speed broadband connectivity, low latency, and greater capacity than previous generations. This technology represents a significant evolution from 4G, enabling a higher number of devices to be connected, providing wider coverage, and offering faster connection speeds.

The 5G has the potential to transform society in many ways, allowing for better connectivity for Internet of Things (IoT) devices, the use of autonomous vehicles, and the creation of smart cities, among other things. However, there are also concerns regarding security and privacy, as well as potential health consequences from the millimeter waves used by the 5G technology.

Video streaming protocols play a crucial role in harnessing the immense potential of 5G technology. As the fifth generation of mobile network technology revolutionizes connectivity with its high-speed broadband, minimal latency, and expanded capacity, it opens up exciting opportunities for various sectors. This includes enabling seamless streaming of high-quality video content, which relies on efficient protocols to transmit data smoothly and ensure a seamless user experience.

The capabilities of 5G technology are pivotal for broadcast transmission methods, particularly for mobile receivers. This enables the replacement of traditional broadband methods, which often encounter numerous issues, especially in the context of video streaming.

The chapter opens with an explanation of how the 5G high-level architecture works in Section 2.1. It continues by detailing the protocol stack between the user and antenna in Section 2.2, offering a comprehensive analysis from a low-level perspective. Moving forward, Sections 2.3 and 2.4 introduce the strengths and various applications of 5G. In Section 2.5 is presented an overview of the commonly used video streaming protocols. Continuing, Section 2.6 highlights different types of transmission technologies. Finally, the chapter concludes with a summary (Sec. 2.7), where it is explained how these technologies are interconnected.

2.1. 5G architecture

The 5G architecture is outlined in a set of documents that belong to the 38 series [14] of the 3rd Generation Partnership Project (3GPP) specifications.

At a high level, the architecture can be divided into two main components: the 5G Core and the 5G Radio Access Networks (RAN), as shown in Fig. 2.1.

The 5G Core is responsible for managing the overall network and providing services such as authentication, policy enforcement, and network slicing. It is a cloud-native architecture designed to be highly scalable and flexible, enabling operators to deliver a wide range of services to their customers.

On the other hand, the 5G RAN is responsible for providing the wireless connectivity between end-user devices and the core network. It includes the gNodeB (gNB) base stations, which transmit and receive wireless signals to and from User Equipment (UE), as well as the backhaul network.

The range of radio frequencies utilized by 5G networks is wider compared to that of 4G LTE networks. Therefore, 5G requires new types of nodes and Radio Access Technologies (RATS) for utilizing this expanded spectrum.

By using virtualization, networking functions can be decoupled from the underlying hardware, enabling them to be upgraded as technology evolves. This characteristic makes 5G infrastructure a form of Virtual RAN (vRAN).

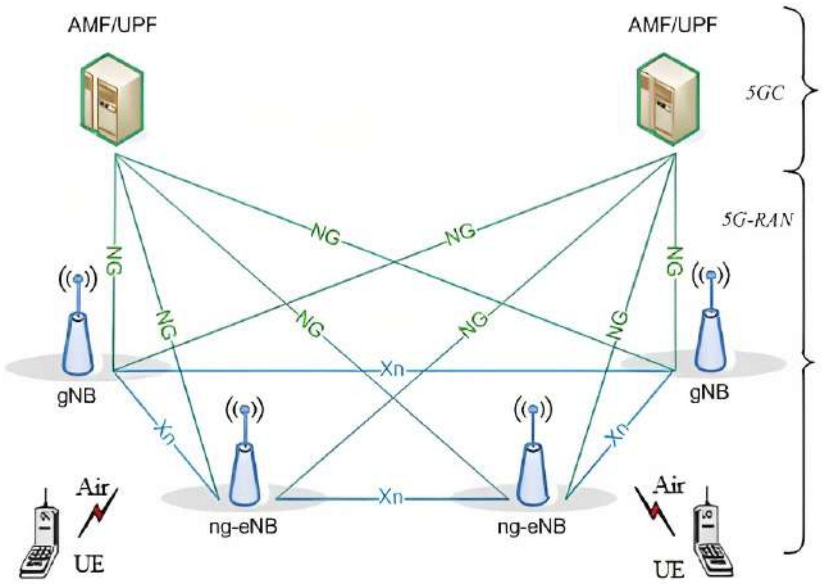


Figure 2.1: 5G Overall Architecture [16]

The antenna and accompanying software in a 5G RAN enable the support of 5G New Radio (NR), which is a RATS employed by 5G networks. There are two types of radio base station nodes in 5G networks: gNB and ng-eNB (Fig. 2.1). Both of these nodes allow devices to connect to the 5G core network, but while gNB allows the connection using the 5G Radio Interface, ng-eNB instead allows 4G LTE devices to connect to 5G Core network using 4G Radio Interface.

Shifting attention to 5G Core network, a more detailed representation of the architecture (Fig. 2.2) reveals the interconnections between various core network elements through different network reference points. Of particular interest is the user plane connectivity in 5G, referred to as a Protocol Data Unit (PDU) session. This user plane connectivity originates from the mobile device, passes through the gNB, reaches the User Plane Function (UPF), and ultimately connects to the data network.

The user plane connectivity associated with a specific PDU session is exclusive to the device utilizing it; other devices in the network do not share this connectivity. To ensure Quality of Service (QoS) within the PDU session, QoS flows are employed.

A QoS flow represents a stream of user plane traffic that receives a specific level of QoS. Multiple QoS flows may coexist within a PDU session to accommodate different traffic with various requirements,each characterized by different parameters such as latency, priority, and guaranteed or non-guaranteed bit rate. These flows can be transient and removed if necessary.

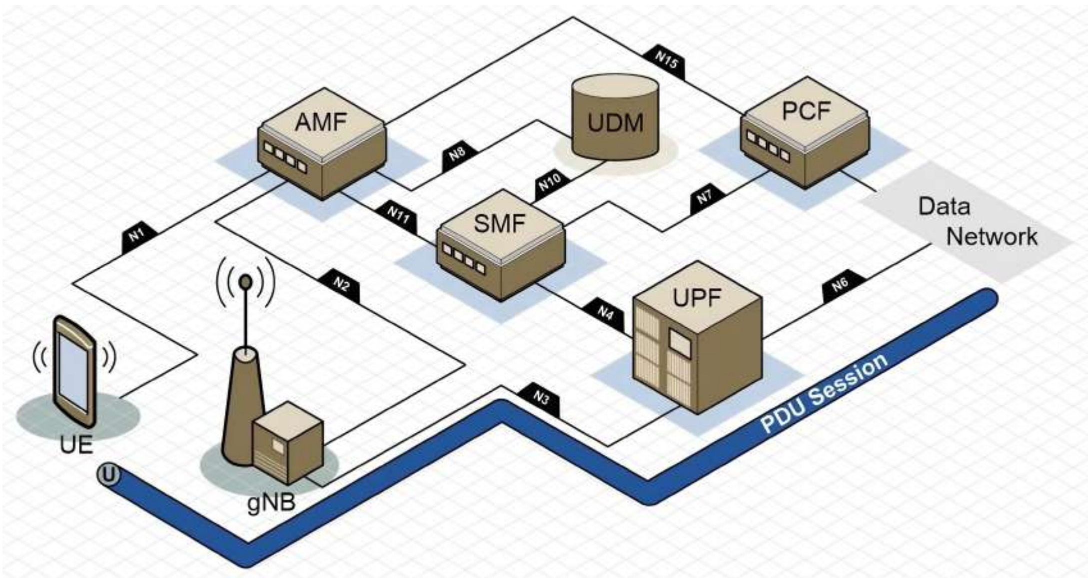


Figure 2.2: 5G Core Network Architecture [24]

Each element of the architecture (Fig. 2.2) is fundamental to ensure the uninterrupted functionality of the PDU session for the subscriber and to enable smooth transition as the subscriber moves across the network. Due to their importance, they will be analysed one by one in the following sections.

2.1.1. Access and Mobility Management Function (AMF)

The Core Access and Mobility Management Function (AMF) plays a similar role to the Mobility Management Entity (MME) in LTE, primarily focusing on managing subscriber mobility. Depending on whether the subscriber is idle or connected, the AMF maintains knowledge of either the tracking area or the potential cell the subscriber is located in.

Furthermore, the AMF assumes vital responsibilities in terms of security and registration. It establishes communication with various subscriber databases to verify the subscriber's eligibility for network access and performs authentication procedures within the network.

2.1.2. Session Management Function (SMF)

In LTE, the MME traditionally handled both mobility management and session management. However, in 5G, these functions have been separated. While the AMF is responsible for mobility management, the Session Management Function (SMF) specifically focuses on session management.

The SMF oversees the establishment, modification, and termination of PDU sessions. It directly interacts with the Policy Control Function (PCF) to determine whether a particular user data session can proceed. Moreover, the SMF plays a crucial role in establishing the actual connectivity of the PDU session: selects the appropriate UPF for routing the multiple individual connections that must be established within the network.

Additionally, if the data session is IP-based, the SMF assigns an IPV4 or IPV6 address. However, it should be noted that PDU sessions in 5G can also be based on purely Ethernet or unstructured data, not limited to IP as in LTE.

2.1.3. User Plane Function (UPF)

User Plane Function (UPF) serves as an anchor point for NG-RAN mobility. While moving across the RAN, transitioning from one gNB to another, the UPF remains a constant anchor point into the core network. Consequently, the user plane connectivity consistently runs from the gNB to the UPF.

Due to its direct involvement with the user plane, the UPF assumes an essential role in enforcing QoS measures. It ensures that the appropriate data is directed down the designated QoS flow and implements relevant policies.

2.1.4. Unified Data Management (UDM)

The Unified Data Management (UDM) acts as a centralized repository of subscriber information, playing a vital role in Access Authorization, storing and managing the subscriber's security keys. Additionally, the UDM is involved in Registration and Mobility Management, keeping track of the subscriber's attachment to a specific AMF.

Moreover, the UDM holds the Data Network Profile or profiles. These profiles contain essential details about the subscriber, including their allowed actions and restrictions. They specify which data networks the subscriber can connect to and outline the corresponding QoS profile they can anticipate upon connecting to these networks.

2.1.5. Policy Control Function (PCF)

The Policy Control Function (PCF) operates on a dynamic basis, making policy decisions based on current network conditions. Before establishing a PDU session to a specific data network, for example, the SMF consults with the PCF to assess if any active network conditions might impact the subscriber's service experience.

The PCF considers various factors, such as the presence of subscribers in a particular geographical location or their current cell, to determine if actions like throttling or denying PDU session connectivity are necessary. With its dynamic capabilities, the PCF can modify both mobility and session-related service aspects, playing a significant role in the overall ecosystem.

2.2. 5G protocol stack

By analysing the connection between UE and gNB in detail, it is possible to study the 5G protocol stack.

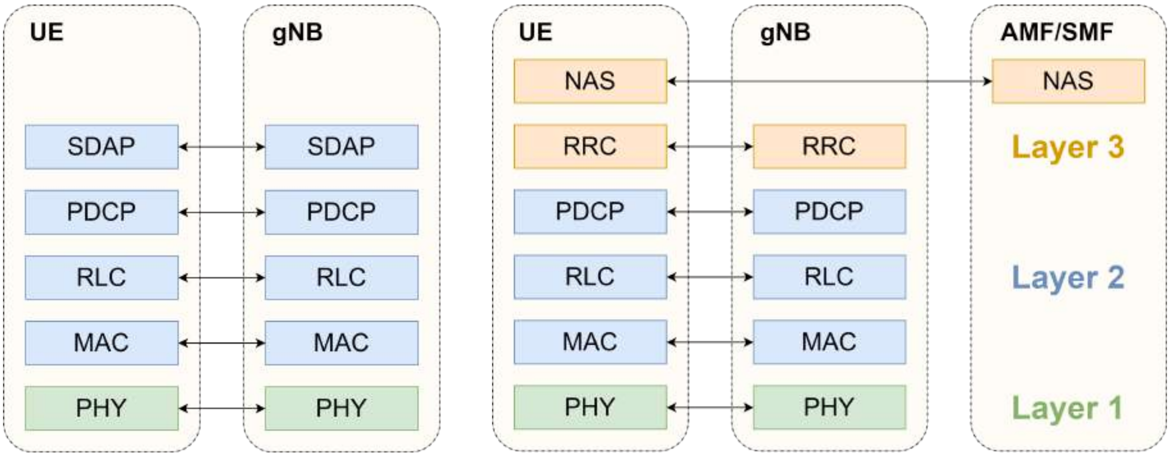
First of all, it should be specified that there are two different types of planes with different responsibilities:

- User plane: responsible for transferring application data between the end user and the application server

- Control plane: responsible for transferring signalling messages

As shown in Fig. 2.3, each plane has a different protocol stack, even though they share part of the structure. In particular, the user plane has only the First and Second Layer, while the control plane also has the third.

In the following sections, the functionalities of the various layer components are described in detail.



(a) User Plane Protocol Stack (b) Control Plane Protocol Stack

Figure 2.3: 5G Protocol Stack

Layer 1

Physical Layer is crucial for transmitting information over the air interface between the UE and gNB. Cyclic Redundancy Check (CRC) bits are added to each Transport Block at the transmitter to allow error detection at the receiver. Channel coding is applied to generate redundancy and increase resilience to the radio propagation channel.

Fig. 2.4 displays the architecture surrounding Layer 1, which depicts the Physical Layer's interactions with the Medium Access Control (MAC) sub-layer of Layer 2 and the Radio Resource Control (RRC) of Layer 3.

The Physical Layer is responsible for several procedures in the 5G NR network. These procedures include cell search, power control, uplink synchronization and timing control, random access, HARQ, beam management and CSI, sidelink, and channel access.

By controlling the resources in the frequency, time, and power domains, the Physical Layer ensures implicit support for interference coordination in the 5G NR network.

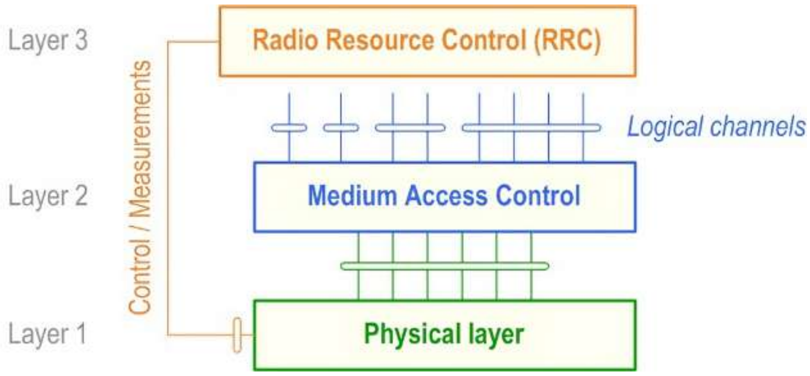


Figure 2.4: Radio interface protocol architecture around the Physical Layer [25]

Layer 2

The Layer 2 protocol stack in 5G consists of several sub-layers: the Medium Access Control (MAC) Layer, the Radio Link Control (RLC) Layer, the Packet Data Convergence Protocol (PDCP) Layer, and the Service Data Adaptation Protocol (SDAP) Layer.

Starting from the bottom, the MAC sublayer is responsible for prioritizing and multiplexing logical channel data received from the RLC Layer, in addition it generates Transport Blocks from the logical channel data and passes them down to the Physical Layer. The MAC Layer supports Hybrid Automatic Repeat Request (HARQ) protocol for reliable data transfer with fast re-transmissions.

The RLC sublayer provides reliable data transmission services by ensuring segmentation and re-segmentation when necessary. It also handles re-transmission requests and duplicate detection. The RLC sublayer can operate in three modes: Transparent Mode, Unacknowledged Mode, and Acknowledged Mode, depending on the requirements of the specific application.

The PDCP sublayer provides header compression, ciphering and integrity protection. Header compression is important because the overheads generated by the higher layers can become large and without compression they would consume valuable air-interface resources. The PDCP sublayer is also responsible for re-ordering packets and providing in-sequence delivery to the higher layers.

Finally, the SDAP sublayer (present only in user plane) provides the mapping between QoS flows belonging to a PDU session (at the top of the SDAP Layer) and Data Radio Bearers (at the bottom of the SDAP Layer).

An example of the Layer 2 data flow is depicted on Fig. 2.5, where a transport block is generated by MAC by concatenating two RLC PDUs from RBx and one RLC PDU from RBy. The two RLC PDUs from RBx each corresponds to one IP packet (n and n+1) while the RLC PDU from RBy is a segment of an IP packet (m).

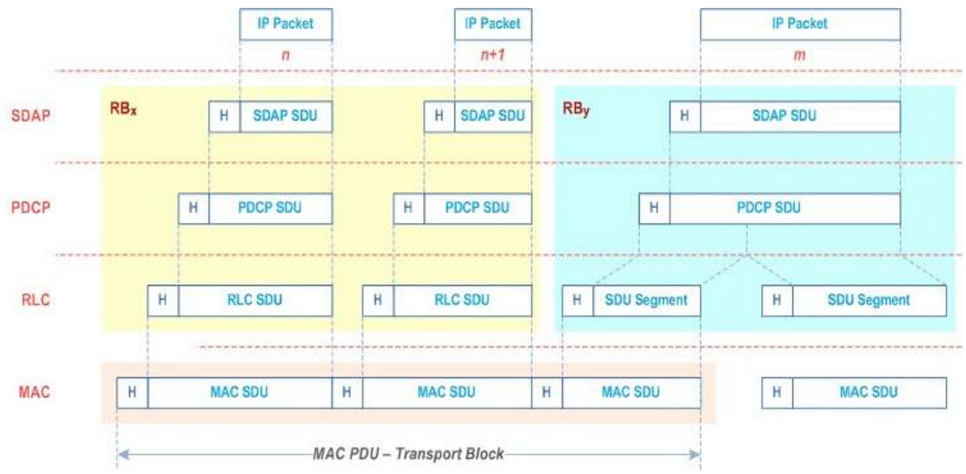


Figure 2.5: Data flow Layer 2 example [25]

Layer 3

Layer 3 of the 5G protocol stack exists only in the control plane and includes Radio Resource Control (RRC) and Non-Access Stratum (NAS).

The RRC signalling protocol operates between the UE and Base Station, while Non-Access Stratum (NAS) signalling protocol operates between the UE and AMF/SMF. Signalling Radio Bearers (SRB) are used for transferring RRC messages, including NAS messages since RRC messages can encapsulate them.

3GPP has specified 4 types of SRB for NR:

- SRB 0 transfers RRC messages with use the Common Control Channel (CCCH) logical channel
- SRB 1,2 and 3 transfers RRC messages with use the Dedicated Control Channel (DCCH) logical channel

There is a mapping between SRB with all possible RRC messages, including both direction (uplink or downlink) and all possible RLC mode (Sec. 2.2).

2.3. 5G strengths

This section highlights the strengths that make 5G a technology that revolutionize the way we communicate and access information. More specifically, these are related to: Spectrum and Frequency (Sec. 2.3.1), Multi-Access Edge Computing (Sec. 2.3.2), Network Function Virtualization (Sec. 2.3.3), Radio Access Networks (Sec. 2.3.4), Network Slicing (Sec. 2.3.5) and Beamforming (Sec. 2.3.5).

2.3.1. Spectrum and Frequency

Multiple frequency bands are now being dedicated to 5G NR. The portion of the radio spectrum with frequencies between 30 GHz and 300 GHz is known as the millimeter wave, since wavelengths range from 1-10 mm. Frequencies between 24 GHz and 100 GHz have been allocated to 5G in multiple regions worldwide.

In addition to the millimeter wave, underutilized UHF frequencies between 300 MHz and 3 GHz and C-band frequencies between 3.7 and 3.98 GHz have also been re-proposed for 5G.

The use of different frequency bands in 5G can be optimized for specific applications. Higher frequency bands offer wider bandwidth but have a shorter coverage range. Millimeter wave frequencies, for example, are well-suited for high-density urban areas but may not be effective for long-distance communication due to their limited range.

2.3.2. Multi-Access Edge Computing (MEC)

Multi-Access Edge Computing (MEC) is a crucial component of the 5G infrastructure that leverages cloud computing to bring applications closer to end users and their devices. This allows for quicker content delivery by bypassing long-distance network paths.

MEC characteristics include low latency, high bandwidth, and real-time access to RAN information. 5G networks based on 3GPP 5G specifications are an ideal environment for MEC deployment, as these specifications allow for edge computing enablers. The distribution of computing power enabled by MEC allows for the high volume of connected devices inherent in 5G and IoT deployment, in addition to the latency and bandwidth benefits.

However, the convergence of RAN and core networks will require new approaches to network testing and validation by operators.

2.3.3. Network Function Virtualization (NFV)

Network Function Virtualization (NFV) is a technique that separates software from hardware by using virtualized instances to replace various network functions like routers, firewalls, and load balancers. This eliminates the need for expensive hardware investments and speeds up installation times, allowing for faster revenue generation.

NFV is an important component of the 5G ecosystem as it virtualizes appliances within the network, including the network slicing technology that enables the simultaneous running of multiple virtual networks. By utilizing virtualized computing, storage, and network resources that are customized based on the applications and customer segments, NFV addresses other 5G challenges.

2.3.4. Radio Access Networks (RAN)

The idea of NFV is expanded to the RAN through network disaggregation promoted by groups like Open Radio Access Network (O-RAN). O-RAN architecture facilitates the deployment of new RAN features and technology at scale by promoting open interfaces and open-source development practices. This approach provides more flexibility and competition opportunities.

Network disaggregation also allows more components of the network to be virtualized, making it possible to scale and enhance the user experience quickly as capacity grows. Virtualized RAN is essential for managing hardware and software costs in the rapidly expanding ecosystem of IoT applications.

2.3.5. Network Slicing

Network slicing is a crucial element for realizing the full potential of 5G architecture. This technology adds an extra dimension to the NFV domain by enabling multiple logical networks to run concurrently on top of a shared physical network infrastructure. This capability supports 5G architecture by creating end-to-end virtual networks that include networking and storage functions.

Network slicing is particularly beneficial for applications like the IoT, where the number of users may be high, but the overall bandwidth demand is low.

Since each 5G vertical has unique requirements, network slicing is a vital design consideration for 5G network architecture. Network slicing offers a high level of customization, optimizing operating costs, resource management, and flexibility of network configurations.

Moreover, network slicing enables expedited trials for potential new 5G services and faster time-to-market.

2.3.6. Beamforming

Beamforming is a revolutionary technology that plays a crucial role in the success of 5G. Unlike conventional base stations that transmit signals in multiple directions, regardless of the position of targeted users or devices, beamforming utilizes Multiple-Input Multiple-Output (MIMO) arrays that include numerous small antennas combined in a single formation. This enables signal processing algorithms to determine the most efficient transmission path to each user, with individual packets sent in multiple directions and choreographed to reach the end user in a predetermined sequence. An illustrative drawing is shown in Fig. 2.6.

The millimeter wave, used for 5G data transmission, is susceptible to free space propagation loss and diffraction loss due to the higher frequencies and lack of wall penetration. However, the smaller antenna size allows for larger arrays to occupy the same physical space. With each of these smaller antennas potentially adjusting or reassigning beam direction several times per millisecond, massive beamforming becomes more feasible for 5G bandwidth challenges. Moreover, larger antenna density in the same physical space allows for narrower beams, thereby providing high throughput and more effective user tracking.

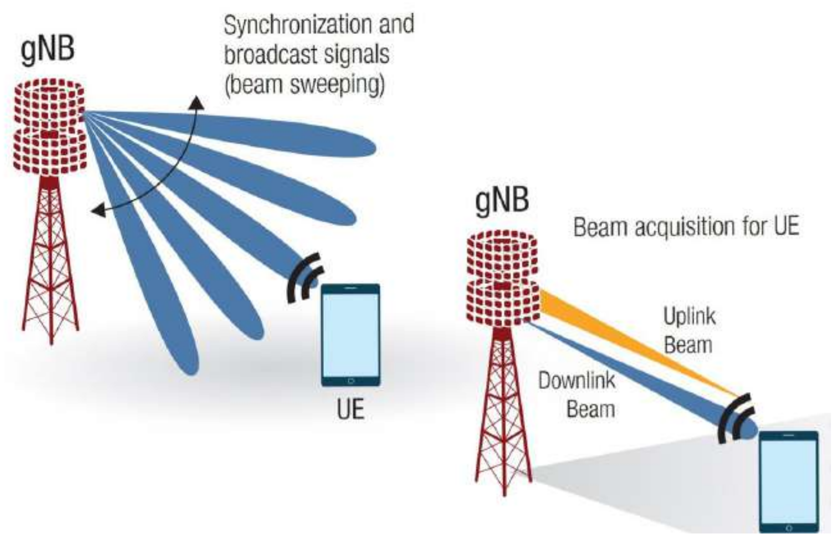


Figure 2.6: 5G Beamforming [28]

2.4. 5G applications

The next-generation 5G wireless network is set to revolutionize the way we connect to the world around us, providing not just faster speeds and increased capacity but also opening up a whole new range of possibilities for innovative applications and use cases. From gaming to government, everyone stands to benefit from the convergence of 5G connectivity, intelligent edge, and IoT technologies.

With its ability to move data at unprecedented speeds, 5G promises to transform a wide range of industries, including retail, education, transportation, entertainment, smart homes, and healthcare. The potential impact on the global economy is immense, with experts predicting trillions of dollars in revenue in the coming years.

2.4.1. High-speed mobile network

One of the most significant applications of 5G technology is on high-speed mobile networks. With its supercharged wireless network, 5G is capable of supporting data download speeds of up to 10 to 20 GBPS, which is equivalent to a fiber-optic internet connection accessed wirelessly. This is a significant improvement compared to conventional mobile transmission technologies, enabling voice and high-speed data to be simultaneously transferred efficiently.

With 5G, mobile downloads will be faster, always-on, always connected, and more responsive. The network will also enable secure access to cloud storage, enterprise applications, and the ability to run powerful tasks with greater processing power virtually.

2.4.2. Entertainment and multimedia

The implementation of 5G wireless networks will revolutionize the entertainment and multimedia industry. High-definition streaming of 4K videos and live events with crystal clear audio clarity will be possible without interruptions. 5G networks will offer 120 frames per second, high resolution, and higher dynamic range video streaming. This will enable a better audiovisual experience for users, and augmented reality and virtual reality will also be powered by the powerful 5G network. HD virtual reality games will become more popular, and the gaming experience will improve significantly.

The implementation of 5G wireless networks will also deliver services such as high-definition streaming video without buffering, reducing slowdowns during usage spikes, allowing users to stream sports events or their favorite shows without interruption.

2.4.3. Industrial IoT (IIoT)

The Industrial Internet of Things (IIoT) is a broad area for development that is being supercharged by 5G wireless network technology. With its low latency and high network capacity, 5G has the potential to eliminate the biggest limitations to IIoT expansion. This pairing of 5G and IIoT can impact nearly every industry and consumer.

One industry sector that can make use of 5G technology is logistics and shipping. With smart 5G technology, goods can be tracked and fleet management can be done more efficiently. Centralized database management, staff scheduling, real-time delivery tracking and reporting can also be improved. Compared to conventional mobile networks, 5G has a faster network with the capability to connect more devices at any given time.

In the future, industries will depend on smart wireless technologies like 5G and LTE advanced for efficient automation of equipment, predictive maintenance, safety, process tracking, smart packing, shipping, logistics, and energy management. Smart sensor technology offers unlimited solutions for IIoT for smarter, safe, cost-effective, and energy-efficient industrial operations.

5G technology will also be used for agriculture and smart farming in the future. Farmers can track the location of livestock and manage them easily using smart RFID sensors and GPS technology. Smart sensors can be used for irrigation control, access control, and energy management.

2.4.4. Autonomous Driving and Drone Operation

Autonomous driving and drone operation are rapidly evolving areas that can benefit from the capabilities of 5G wireless networks. The high-performance connectivity and low latency of 5G technology can help overcome limitations and expand possibilities for these applications.

Self-driving cars can communicate with surrounding objects and other vehicles on the road in real-time, this communication enables split-second decision making, which is crucial for avoiding collisions and ensuring passenger safety. With the use of smart traffic signs and other IoT devices, self-driving cars can navigate roads more efficiently and with greater safety.

Similarly, 5G network connectivity can revolutionize drone operation in a wide range of applications. Drones are being used in emergency situations to collect important information that can help first responders make informed decisions. With 5G connectivity, drones can transmit data back to the command center in real-time, allowing emergency responders to make faster and better decisions.

2.5. Video streaming protocols

In recent years, video streaming has become a ubiquitous and essential part of our daily lives, as more and more people rely on it for entertainment, education, communication, and business. To ensure a smooth and high-quality streaming experience, adaptive video streaming technologies have emerged as a key solution, allowing video content to be delivered over the internet in a flexible and efficient manner.

Among the most popular and widely used adaptive streaming technologies are HTTP Live Streaming (HLS) and Dynamic Adaptive Streaming over HTTP (DASH), which have been adopted by major streaming platforms such as Netflix, YouTube, and Amazon Prime Video.

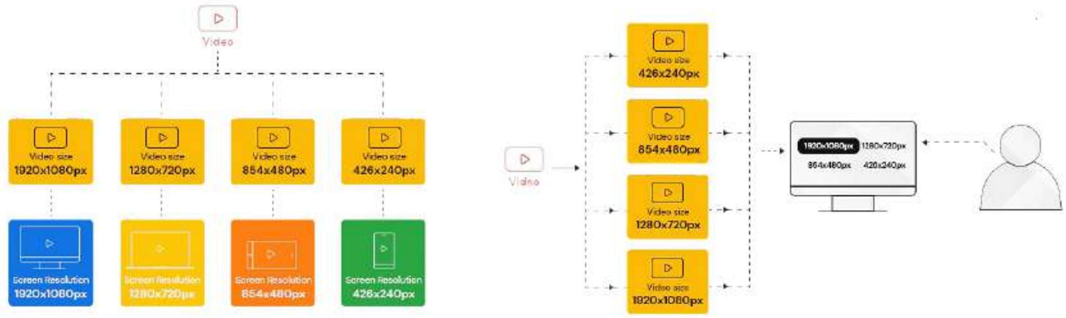
One of the main features of HLS and DASH is that they are HTTP-based Adaptive-BitRate (ABR) streaming communications protocols.

2.5.1. ABR vs MBR

ABR refers to a set of technologies and standards that allow video content to be streamed over the internet in a way that adapts to the network and device conditions of the viewer. ABR protocols dynamically adjust the bitrate and resolution of the video stream based on factors such as available bandwidth, latency, packet loss, and screen size, in order to provide the best possible viewing experience while minimizing buffering and interruptions.

ABR protocols achieve this by segmenting the video content into small chunks that are delivered over the network in response to requests from the client. These chunks are encoded at multiple bitrates, and the ABR protocol switches between the different bitrate versions based on the current network and device conditions. This allows the video stream to adapt in real-time to changing network conditions, providing a seamless viewing experience to the user.

In contrast to ABR (Fig. 2.7), traditional Multi-BitRate (MBR) streaming requires the user to select a fixed bitrate and resolution before playback begins. This means that the video stream cannot adapt in real-time to changes in network conditions, potentially resulting in buffering or interruptions if the user's connection cannot support the selected bitrate.



(a) Adaptive-Bitrate streaming

(b) Multi-Bitrate streaming

Figure 2.7: ABR vs MBR [33]

ABR protocols offer a significant advantage over MBR streaming in terms of flexibility and adaptability, and have become the preferred approach for delivering high-quality video content over the internet.

2.5.2. HTTP Live Streaming (HLS)

HLS is a streaming protocol developed by Apple Inc. and released in 2009. It is designed to work efficiently over a variety of networks, including high-speed broadband/mobile networks and supports a wide range of codecs and container formats, making it compatible with most devices and browsers.

As shown in Fig. 2.8 HLS protocol starts with an *encoder* that codifies video files in the H.264 or H.265 format and audio in AAC, MP3, AC-3, or EC-3. The encoder then encapsulates the data into MPEG-2 Transport Stream or MPEG-TS (.ts) format, which allows it to be carried over HTTP.

The segmented stream is then passed on to the *segmenter*, which divides the stream into fragments of equal length (typically 10 seconds). The segmenter also creates an index file, known as the playlist file (.m3u8), which contains references to the fragmented files. This playlist file is essential in case of an unstable connection or if the user wants to watch parts of the video again.

The *distributor*, which is typically a standard web server, accepts requests from clients and delivers all the resources (.m3u8 playlist file and .ts segment files) needed for streaming. The client requests and downloads all the files and resources, assembling them so that they can be presented to the user as a continuous flow video.

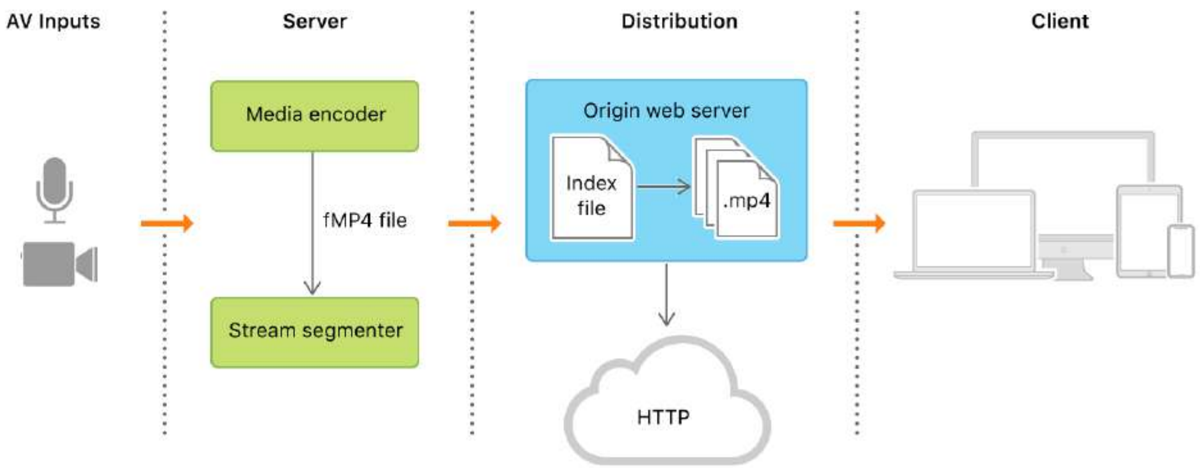


Figure 2.8: HLS flow [34]

The playback software assembles the sequence of the downloaded video segments to allow continued display to the user.

In 2019, Apple introduced Low-Latency HLS (LL-HLS) [36], a new version of the protocol that aims to reduce the latency of video streaming over public networks to below 2 seconds. This makes HLS suitable for live video streaming applications, such as sports and news, where low latency is crucial for viewer engagement. LL-HLS achieves low latency by using chunked transfer encoding and HTTP/2 server push, while remaining compatible with existing HLS clients.

HLS is widely used by major streaming platforms [37], including Twitch [38], the world's leading gaming streaming site. Its popularity can be attributed to its compatibility with a wide range of devices and its ability to adapt to changing network conditions.

2.5.3. Dynamic Adaptive Streaming over HTTP (DASH)

Developed by Moving Picture Experts Group (MPEG) and released in 2011, DASH is an open standard protocol that is free to use. The most recent version of DASH was published in 2016. Similar to HLS, DASH is also supported by major streaming platforms such as Netflix, YouTube, and Amazon Prime Video.

DASH follows the same high-level architecture as HLS (Fig. 2.9), with the primary difference being the encoder used. An Media Presentation Description (MPD) file in XML format contains tagged information about media files, such as the location of the video segments and their corresponding bitrate and resolution options. The MPD file acts as a manifest file that specifies the media components of the stream.

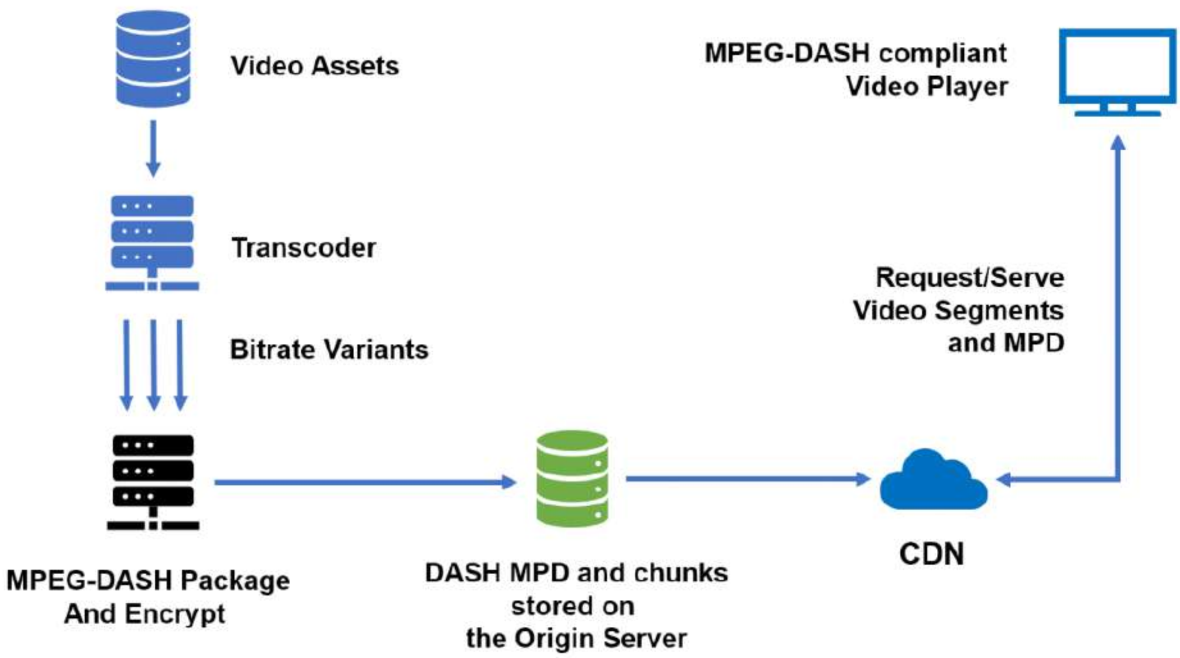


Figure 2.9: DASH flow [40]

One of the significant advantages of DASH is its ability to support any format encapsulated in .mp4. This means that the protocol is flexible and can be used to stream different types of video content, including high-resolution video, 3D video, and even virtual reality.

The client starts by requesting the MPD file from the server, which provides the necessary information about the available video segments. The client then selects the appropriate video segment based on the network conditions and device capabilities and requests it from the server.

The server sends the requested video segment, which is then assembled by the client along with other segments to create a continuous flow of video playback.

2.5.4. HLS vs DASH

Firstly, HLS specifies the use of certain video codecs (H.264, H.265) and audio codecs, whereas DASH is codec-agnostic. This means that DASH can leverage the latest and most advanced codecs for higher quality broadcasts at lower bitrates.

Secondly, HLS has traditionally used the MPEG-2 transport stream container format, or MPEG-TS (.ts), while DASH uses the MP4 format. This difference in container format may impact the compatibility of the protocol with certain devices and platforms.

Finally, both protocols have traditionally lagged in terms of delivery speed, but new approaches seek to change this. For DASH, this takes the form of the Common Media Application Format (CMAF), whereas Apple now offers the LL-HLS as already anticipated, which promotes latencies below 2 seconds over public networks while remaining compatible with existing clients.

2.5.5. Common Media Application Format (CMAF)

CMAF is an emerging media format designed to address the issue of duplication of content encoding and storage. Specifically, it aims to improve cross-compatibility between the HLS and DASH protocols by specifying the same container format for both (Fig. 2.10), which is the fragmented MPEG (fMP4) format. With CMAF, content distributors can encode and store their audio and video data only once, making it easier and more cost-effective to deliver their content to a wide range of devices. In addition, CMAF is expected to help reduce latency in streaming by providing around 3-5 seconds latency, which is a significant improvement compared to traditional HLS and DASH protocols.

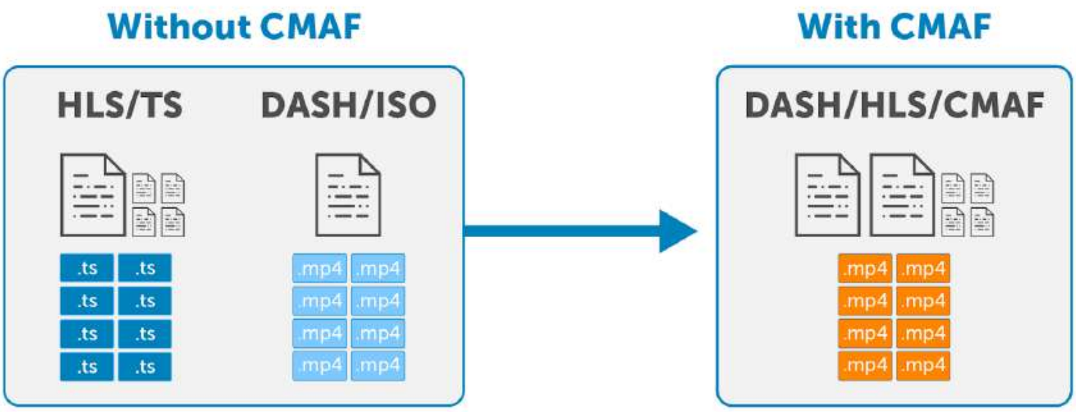


Figure 2.10: CMAF difference [39]

2.6. Types of transmission technology

The significance of 5G technology's capabilities cannot be overstated when it comes to revolutionizing broadcast transmission techniques, especially in the realm of mobile receivers. This innovation facilitates the substitution of conventional broadband approaches, a realm with significant limitations, particularly in the context of video streaming.

2.6.1. Broadcast

Broadcast technology, also known as terrestrial networks, is a method of transmitting messages to a large number of recipients simultaneously (one-to-many). It is used in radio and television broadcasting, as well as other electronic media outlets, to distribute content from a centralized source.

In a broadcast network, a message sent by a node is received by all other nodes connected to the network and sharing a common medium of communication. This allows for a simple method of transferring messages to all recipients simultaneously without the need for complex routing procedures of switched networks. As a result, broadcast networks have a single communications channel.

This single communication channel is shared by all machines present on the network, and short messages or packets sent by any machine are received by all others on the network.

There are advantages and disadvantages to using broadcast networks. One of the advantages is that packets are transmitted and received by all devices on the network simultaneously, making transmission efficient for broadcasting news and emergency alerts. However, this type of communication do not allow for message personalization, making them unsuitable for some applications.

2.6.2. Broadband

Broadband is a type of private data connection that securely connects two or more locations for private data services. Unlike broadcast networks, this networks allow for a direct connection between two nodes or endpoints of communication.

Broadband networks are commonly used for transmitting personalized data between two locations, that may be sensitive and confidential. The network includes various connections among individual pairs of machines. Packets present on these networks may need to go through intermediate computers before they reach the desired destination computer. Therefore, routing algorithms are essential in point-to-point connections.

Internet is a prime example of a large-scale broadband network where there is a single connection between the server and each client, since each user may require different resources. These connections are managed one at a time, or in parallel over the limited number of server cores. As the number of connections and requests increase, the performance of the server decreases, which in turn increases the response time.

In summary, broadband networks are useful for exchanging personalized information between a source and a user, but their performance are influenced by network traffic. On the other hand, broadcast networks can maintain high performance even on a large scale, but they do not allow for customization, meaning that all users receive the same content.

2.7. Summary

As we have seen, one of the main applications of 5G is related to the entertainment and multimedia industry. This can revolutionise in particular the transmission of live streaming events, which is currently done via the Internet with the limitations of broadband technology (reduced performance as traffic increases), opening the door to a broadcast system. In the next chapter will be presented a technology developed by 5G-MAG that enables video transmission and reception with HLS/DASH systems via 5G.

3 | 5G Media Action Group (MAG)

The 5G Media Action Group (5G-MAG) [45] is an independent not-for-profit association that promotes collaboration between the media and ICT industries. Based in Geneva, Switzerland, the group aims to drive the market-oriented implementation of solutions for the connected media world, utilizing global internet and 5G access technologies.

The group's work encompasses the conception of use cases, services, and applications, up to the implementation of proof-of-concepts and products.

Stakeholders across the end-to-end value chain can participate, including content and service providers, network operators, technology solution suppliers, software developers, equipment manufacturers, R&D organizations, universities, regulators, and policy makers. The group operates through member-driven and contribution-driven work items, which include market-driven services, applications, and use cases, specifications, profiles, recommendations, guidelines, open-source reference tools, trials, and projects.

Currently, 5G-MAG is focused on the application of 5G for content creation, production, distribution, and consumption.

5G-MAG Reference Tools (RT) Development Programme is an initiative aimed at developing a common ecosystem of open software reference tools to support the implementation and interoperability of 5G media technologies. The program is driven by an open developers' community sponsored by 5G-MAG members, which provide the necessary funding, define priorities and coordinate development. The reference tools developed are intended to simplify workflows, provide support and abstraction, and facilitate the exchange between developers and standardization experts.

Multimedia Broadcast/Multicast Service (MBMS) is a point-to-multipoint service in which data is transmitted from a single source entity to multiple recipients. The MBMS bearer service offers two modes, namely broadcast mode and multicast mode. In the scope of the 5G-MAG Reference Tools (RT) the focus is on the broadcast mode.

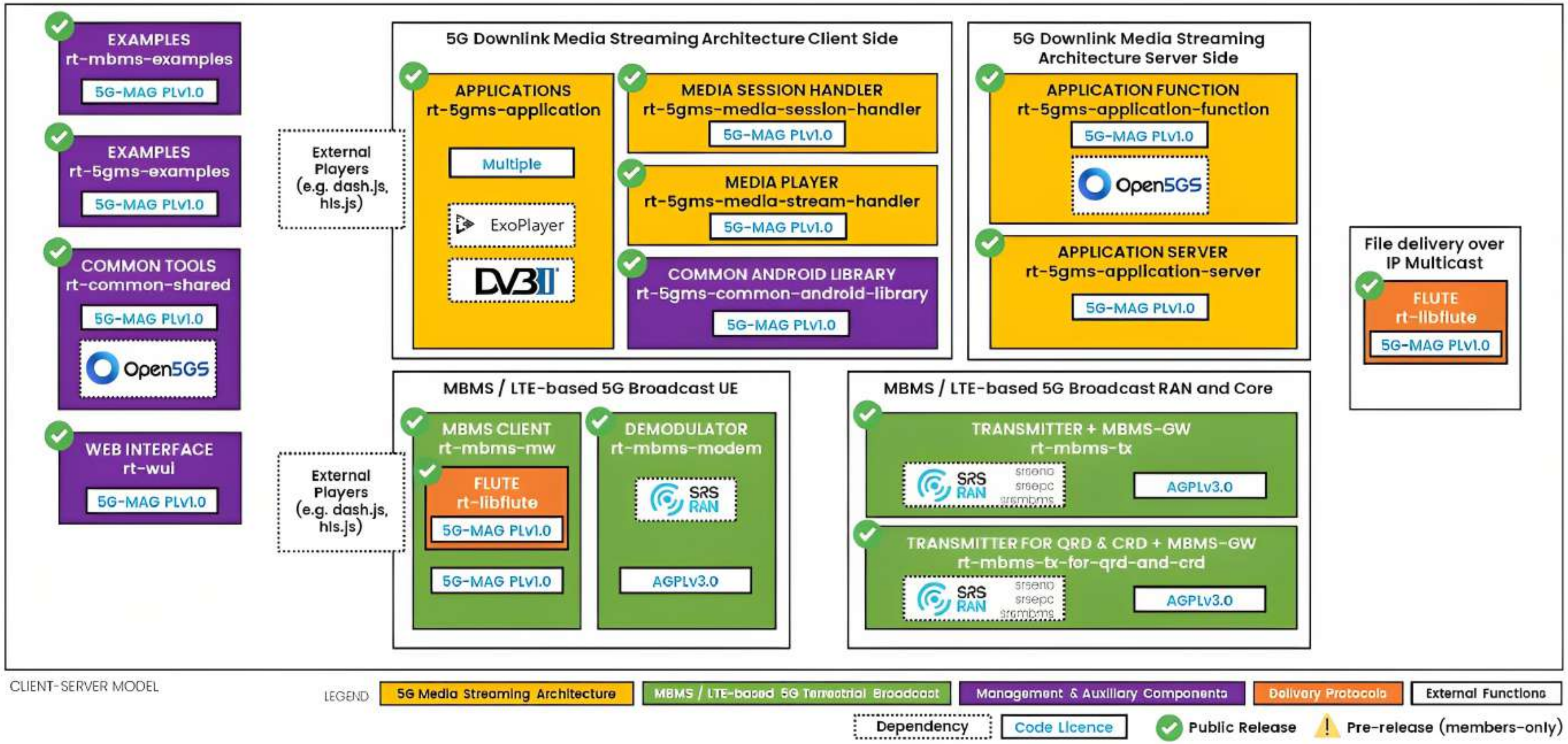


Figure 3.1: 5G-MAG Reference Tools - GitHub repositories and licences [45]

The 5G-MAG Reference Tools comprises several projects that enable a wide range of capabilities, as depicted in Figure 3.1. These capabilities include the transmission of 5G signals using "MBMS/LTE-based 5G Broadcast RAN and Core" technology, as well as the reception of these signals through the use of the "MBMS Client" and "Demodulator" Github repositories.

3.1. Architecture overview

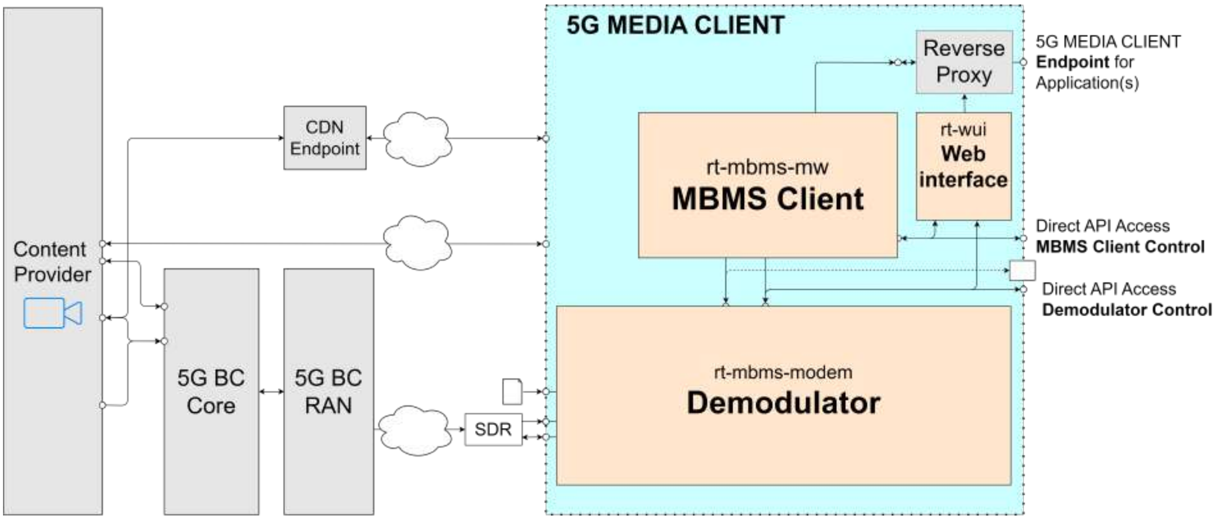


Figure 3.2: 5G-MAG RT Overview [45]

In our specific scenario, we focus on the reception of the 5G signal, which takes place in the 5G Media Client block, as shown in Fig. 3.2 and 3.3.

The signal, in its RAW format, is received by the Software-Defined Radio (SDR) (or from a sample file during testing), and then passed on to the Demodulator for demodulation. This block plays a crucial role in converting the 5G Broadcast Channel input signal into IP Multicast output packets, which are then made available to multiple clients through the FLUTE protocol (as explained in Section 3.4.2).

While the function provided by the Demodulator block is useful for any data stream transmitted via 5G, the MBMS Client block specializes in receiving IP Multicast packets and converting them into the selected HLS or DASH format. The received chunks are temporarily saved in a cache and made accessible internal through a RestAPI, as well as an external through a Reverse Proxy.

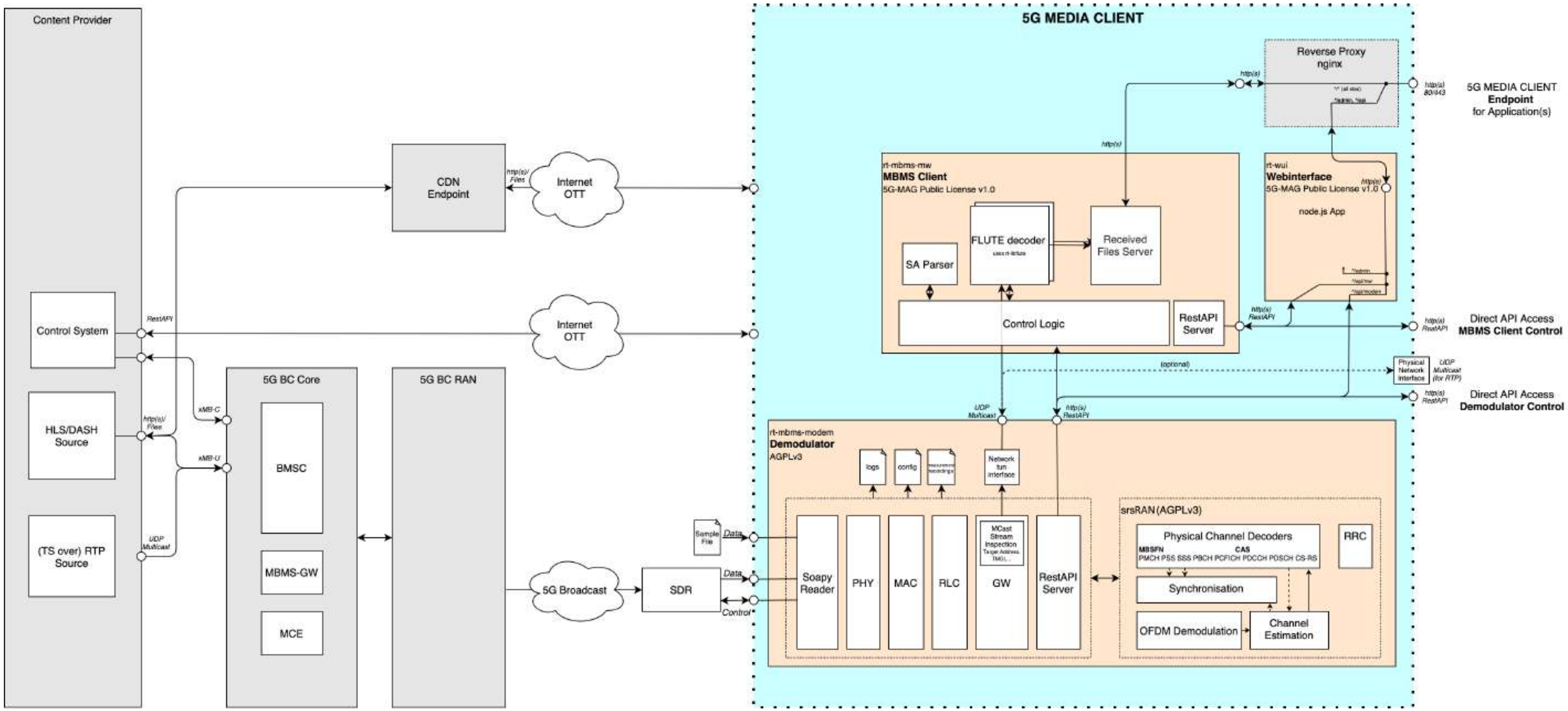


Figure 3.3: 5G Media Client Detailed Architecture [45]

The logical and physical separation of these two blocks is crucial as it allows for a single Demodulator, connected to an antenna (for instance, in a car), to perform the aforementioned conversion for all 5G transmissions received. At the same time, multiple clients can handle different streams, be they video or other types.

The Web Interface represents the final block in the chain, with its main function being to request files from the internal RestAPI and provide access to streaming through a video player. In addition to this core functionality, the Web Interface also displays some control information related to the MBMS Client.

3.2. Software-Defined Radio (SDR)

Software-Defined Radio (SDR) is a transformative technology that revolutionizes wireless communication systems. It combines hardware and software, allowing for the reconfiguration of radio functionalities. SDR architecture consists of an Radio Frequency (RF) frontend and a baseband processing unit. The RF frontend uses Analog-to-Digital Converters (ADCs) and Digital-to-Analog Converters (DACs) to convert analog RF signals to digital samples, in particular to raw In-Phase (I) and Quadrature (Q) samples, collectively known as raw I/Q data. These samples encode both amplitude and phase data, facilitating subsequent digital processing. The baseband processing unit handles modulation, demodulation, encoding, decoding and signal processing.

SDR offers unmatched flexibility, enabling rapid prototyping, testing, and deployment through software updates. It supports multiple communication standards within a single device, promoting interoperability. SDR improves spectrum efficiency by adapting to changing environmental conditions and optimizing spectrum utilization. It also reduces costs by utilizing off-the-shelf hardware and customizable software solutions.

For the purposes of the experiments, RAI used the LimeSDR board [48], while Politecnico di Milano used the USRP B210 board [49].

3.3. Demodulator (rt-mbms-modem)

The MBMS Modem (Fig. 3.4) is a fundamental component of the 5G-MAG RT, responsible for constructing the lower portion of the toolset. Its primary function is to convert the incoming 5G Broadcast input signal, which is received as raw I/Q data from the SDR, into Multicast IP packets on the output.

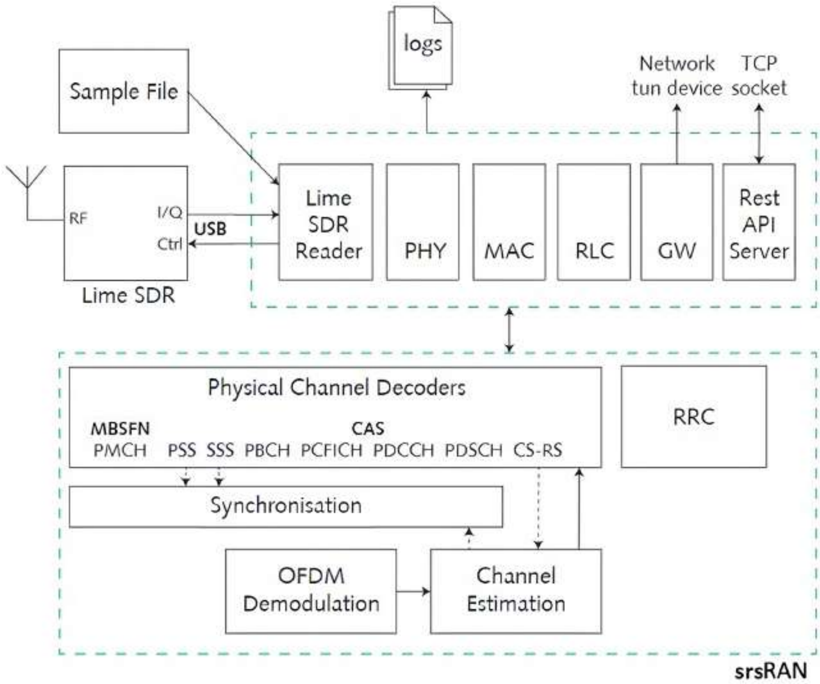


Figure 3.4: MBMS Modem [45]

This critical process enables the transmission of data to multiple users simultaneously, optimizing bandwidth usage and improving the overall performance of the 5G network. The MBMS Modem can run either as a background process or can be started/stopped manually. Configuration of the MBMS Modem can be done either in the configuration file or via the RestAPI, providing flexibility and convenience in adapting to various scenarios.

The main components of the MBMS Modem are implemented as modules for a better overview and to easier improve parts later:

- **Reception** of I/Q data from the Lime SDR Mini, for test purposes the real data can be replaced with data from a previously recorded sample file
- **PHY:** synchronization, Orthogonal Frequency-Division Multiplexing (OFDM) demodulation, channel estimation, decoding of the physical control and user data channels
- **MAC:** evaluation of Downlink Control Indicator (DCI), Continuous Flow Intersection (CFI), System Information Block (SIB) and Master Information Block (MIB). Decoding of Multicast Control Channel (MCCH) and Multicast Traffic Channel (MTCH)
- Read out settings from the **configuration file**

- **RLC/GW:** receipt of MTCH data, output on tun network interface
- **Rest API Server:** provides an HTTP server for the RESTful API
- **Logging** of status messages via syslog

The MBMS Modem is implemented as a standalone C++ application which uses some parts of srsRAN library [51]. In order to use functional extensions and adjustments in srsRAN are necessary:

- **phy/ch_estimation/:** implementation of channel estimation and reference signal for subcarrier spacings 1.25 and 7.5 kHz
- **phy/dft/:** Fast Fourier Transform (FFT) for subcarrier spacings 1.25 and 7.5 kHz
- **phy/phch/:** MIB1-MBMS extension
- **phy/phch/:** support for subcarrier spacings 1.25 and 7.5 kHz
- **phy/sch/:** Bit Error Rate (BER) calculation added
- **phy/ue/:** dynamic selection of sample rate/number of Physical Resource Block (PRB) to support sample files and FeMBMS-Radioframestructure
- **asn1:** support for subcarrier_spacing_mbms_r14

3.3.1. srsRAN

SRS offers the srsRAN Project as an open-source 5G CU/DU, which provides a complete RAN solution that is fully compliant with 3GPP and O-RAN Alliance specifications. This project comprises the entire L1/2/3 stack and has minimal external dependencies, making it highly portable across various processor architectures. The software is scalable, ranging from low-power embedded systems to cloudRAN, and offers a potent platform for research and development of mobile wireless technology.

3.4. MBMS Client (rt-mbms-mw)

The MBMS Middleware utilizes UDP multicast IP packets from the MBMS Modem.

When the payload contains FLUTE decoded content, such as files like Service Announcement, DASH, and HLS, the Middleware decodes the packets with its FLUTE/ALC decoder into files. The Middleware also includes a web-cache server, allowing each service to be available like a CDN publishing point, complete with manifest and segment files.

The FLUTE/ALC decoder is also available as a separate repository, providing encoding and decoding functionalities (rt-libflute [53]).

The main components of the MBMS Client are as follows (as shown in Fig. 3.3):

- **Control Logic:** controls the operations of the program
- **FLUTE/ALC decoder:** if content (files, i.e. Service Announcement, DASH, HLS) is encoded with FLUTE decodes into files (else discard)
- **Received Files Server:** web-cache server
- **RestAPI Server:** management of http (s) requests
- **Software Alghoritm Parser:** parsing the Service Announcement

3.4.1. Service Announcement

A Service Announcement [54] in MBMS refers to the mechanism used to inform users about the availability of MBMS user services. This mechanism provides the user with information about the service, including parameters required for service activation such as IP multicast addresses, and possibly other service-related parameters such as service start time.

3.4.2. FLUTE

File Delivery over Unidirectional Transport (FLUTE) [55] is a protocol designed for the unidirectional delivery of files over the Internet, particularly in multicast networks. It builds on the Asynchronous Layered Coding (ALC) protocol, which provides reliable and scalable multicast distribution.

FLUTE is optimized for the efficient delivery of large files, such as multimedia content, and includes features such as congestion control, flow and error control, and file format encapsulation.

It uses ALC, a protocol designed for the delivery of arbitrary binary objects, as its basic transport.

To describe the protocol, firstly it is important to define:

- **ALC/LCT session:** set of logically grouped ALC/LCT channels associated with a single sender sending ALC/LCT packets for one or more objects (files)
- **ALC/LCT channel:** combination of a sender and an address associated with the

channel by the sender (TOI)

The ALC/LCT session and channel are established by the sender and are independent of the receiver, meaning that the sender initiates the session and creates the channels even if no receiver has joined yet. Once a receiver wants to start receiving data, they can join a specific channel to receive the packets sent by the sender. In Fig. 3.5 is a possible example of ALC/LCT sessions and channels.

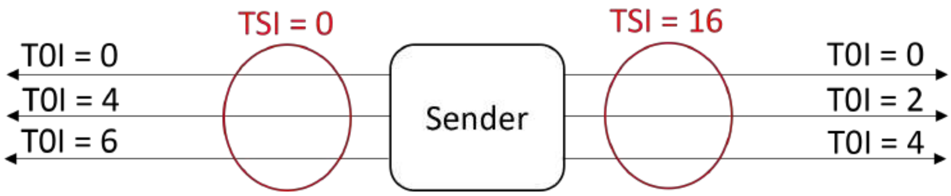


Figure 3.5: ALC/LCT sessions and channels

The combination of the source IP address of the sender and the Transport Session Identifier (TSI) uniquely identifies a session. Receivers use this pair to identify the session that is sending each packet. If a session carries multiple objects (one object per channel), then the Transmission Object Identifier (TOI) field within the ALC/LCT header is used to name the object used to generate each packet.

When FLUTE is used for file delivery over ALC, the ALC/LCT session is referred to as a file delivery session. In this case, the ALC/LCT concept of 'object' denotes either a 'file' or a 'File Delivery Table Instance'.

Fig. 3.6 show examples of rt-mbms-mw in debugger mode, where is possible to see how the 5G-MAG program uses these protocols.

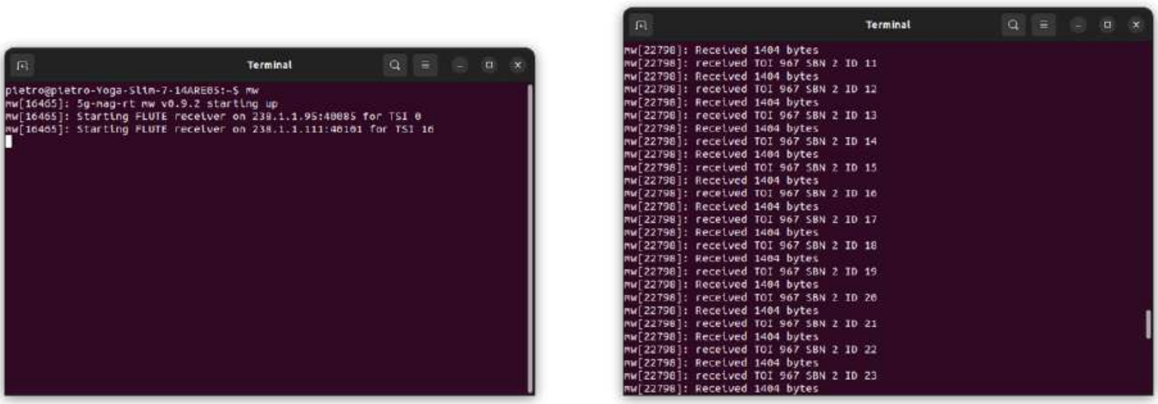


Figure 3.6: rt-mbms-mw in debugger mode

There are some rules that must be followed regarding the TOI:

- TOI field MUST be included in ALC packets sent with a FLUTE session
- TOI value '0' is reserved for File Delivery Table
- Each file in a file delivery session MUST be associated with a TOI (>0)

The File Delivery Table (FDT) is a component of FLUTE that is used to describe the attributes associated with files being delivered within a file delivery session. These attributes can be related to the delivery of the file (TOI, FEC, size of the transmission object carrying the file, etc.) or the file itself (name, identification, location, size, encoding). Some of these attributes are mandatory while others are optional.

The FDT is local to a given file delivery session and provides a mapping of a TOI to the file description entry for each file appearing within the session. Each file description entry in the FDT must include the TOI for the file and a URI identifying the file.

When a client joins an active file delivery session, it may receive data packets for a TOI greater than zero before receiving any FDT Instance. This is a transient situation and the client should discard these packets.

The FDT is delivered within the file delivery session as FDT Instances, which contain one or more file description entries of the FDT. Each FDT Instance can be equal to, a subset of, a superset of, overlap with, or complement any other FDT Instance. Each FDT Instance contains at least a single file description entry and at most the exhaustive set of file description entries of the files being delivered in the file delivery session.

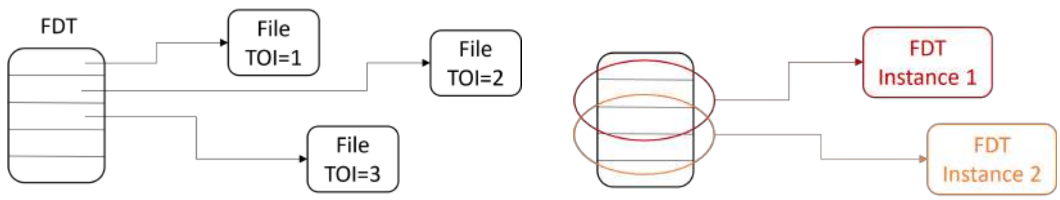


Figure 3.7: File Delivery Table structure

Following rules define the dynamics of the FDT Instances:

- There MUST be a file description entry included in at least one FDT Instance sent within the session
- An FDT Instance MAY appear in any part of the file delivery session, and packets for an FDT Instance MAY be interleaved with packets for other files or other FDT Instances within a session

- The TOI value of '0' MUST be reserved for delivery of FDT Instances
- The FDT Instance is identified by its FDT Instance ID

The ALC packet structure that includes information about the FDT instance is modified with an additional header called EXT_FDT (as shown in Fig. 3.9b). This new header contains the unique identifier (FDT Instance ID) that distinguishes FDT instances within a file delivery session.

In the rt-mbms-mw system each FDT instance is a set of information related to three files.

Before receiving each file, the recipient is sent an FDT Instance ID indicating which file is about to be received. An FDT Instance with the same content is sent three times before each file is received. Before the fourth file is received, the content of the FDT Instance changes and remains constant for the next two files.

The information contained within the FDT instance is only used for the file that is currently being received. This ensures that each file transfer is properly managed and that the recipient has the necessary information to receive and process each file in the correct order.

An example of FDT instance in rt-mbms-mw is shown in Fig. 3.8.

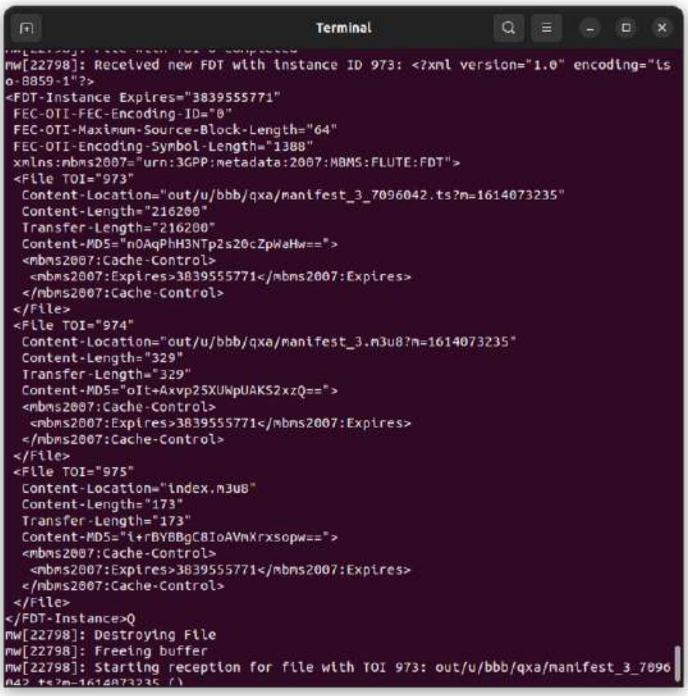
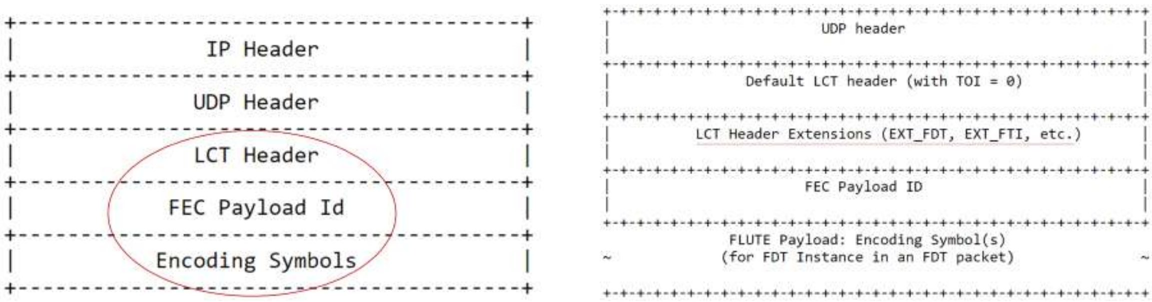


Figure 3.8: FDT instance in rt-mbms-mw

3.4.3. ALC/LCT

Asynchronous Layered Coding (ALC) [56] is a content delivery protocol that provides reliable and congestion-controlled asynchronous delivery of content to an unlimited number of concurrent receivers from a single sender. It combines the Layered Coding Transport (LCT)), multiple rate congestion control, and the Forward Error Correction (FEC) to achieve this. ALC is designed to be massively scalable and can deliver content even in the presence of network congestion and packet loss.



(a) Standard (b) With FLUTE

Figure 3.9: ALC Packet Format [56, 57]

LCT Building Block [57] is a transport layer protocol that supports reliable content delivery and stream delivery protocols. LCT is primarily designed for IP multicast protocols, but it can also support unicast protocols. LCT works with congestion control that enables multiple rate delivery to receivers, and it can also work with coding techniques that ensure reliable delivery of content.

The ALC packet is composed of a series of headers before the Encoding Symbols, LCT Header is the most important and will be explained in detail in the next section, the FEC Payload Id is used for Forward Error Correction. When using this protocol with the FLUTE protocol, an additional header is added that specifies an additional identifier (EXT_FDT, EXT_FTI, etc.).

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   V   | C |PSI|S| O |H|Res|A|B|   HDR_LEN     | Codepoint (CP)|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Congestion Control Information (CCI, length = 32*(C+1) bits)  |
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Transport Session Identifier (TSI, length = 32*S+16*H bits)  |
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Transport Object Identifier (TOI, length = 32*O+16*H bits)  |
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                Header Extensions (if applicable)              |
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3.10: Default LCT Header Format [57]

Fig. 3.10 shows the composition of Default LCT Header Format, in detail:

- **LCT version number (V):** 4 bits
- **Congestion control flag (C):** 2 bits = indicates the Congestion Control Information (CCI) field length
- **Protocol-Specific Indication (PSI):** 2 bits
- **Transport Session Identifier flag (S):** 1 bit = TSI length
- **Transport Object Identifier flag (O):** 2 bits = TOI length
- **Half-word flag (H):** 1 bit = The TSI and the TOI fields are both multiples of 32 bits plus 16*H bits in length
- **Reserved (Res):** 2 bits
- **Close Session flag (A):** 1 bit = MAY set A to 1 when termination of transmission of packets for the session
- **Close Object flag (B):** 1 bit = same but for object
- **LCT header length (HDR_LEN):** 8 bits
- **Codepoint (CP):** 8 bits = information on the codec being used for the packet payload

3.5. Web Interface (rt-wui)

The 5G-MAG Reference Tools Webinterface (rt-wui) is a powerful tool designed to provide a graphical interface for processes, specifically the MBMS Modem, MBMS Middleware, and Application.

With its user-friendly interface, the rt-wui collects and displays essential information from the respective processes, enabling simple measurements and standalone device applications such as set-top boxes and mobile phone/tablet showcases. The rt-wui is divided into three tabs, each for the three processes, and is accessible via http(s), making it perfect for remote monitoring. This innovative tool simplifies the monitoring process, providing an effective solution for keeping track of the performance of 5G-MAG Reference Tools processes.

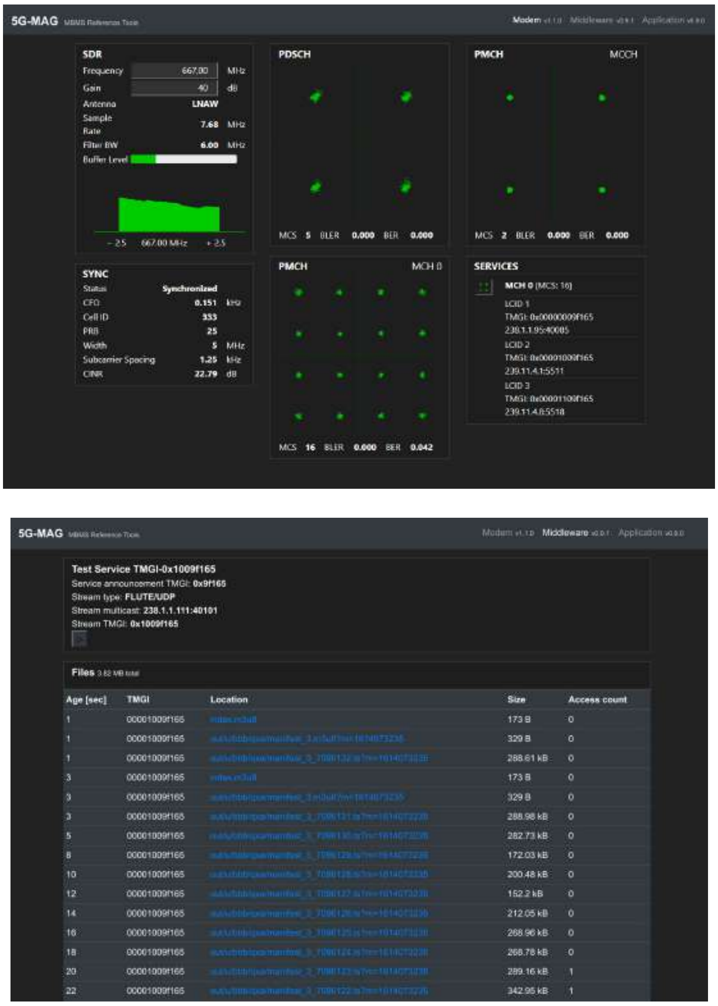


Figure 3.11: Web Interface

4 | Seamless Switching Application (SSA)

The integration of broadband and broadcast services has been achieved through the use of an additional application layer known as the Seamless Switching Application (SSA), which is running on the receiver and has been developed by Politecnico di Milano. Its primary purpose is to ensure a seamless and uninterrupted video streaming experience for the end HLS client.

4.1. Overall architecture

The high-level architecture (Fig. 4.1) of this application comprises an HTTP server that responds to video streaming requests via three channels: broadband (BB), broadcast (BC), and the switching channel (BS).

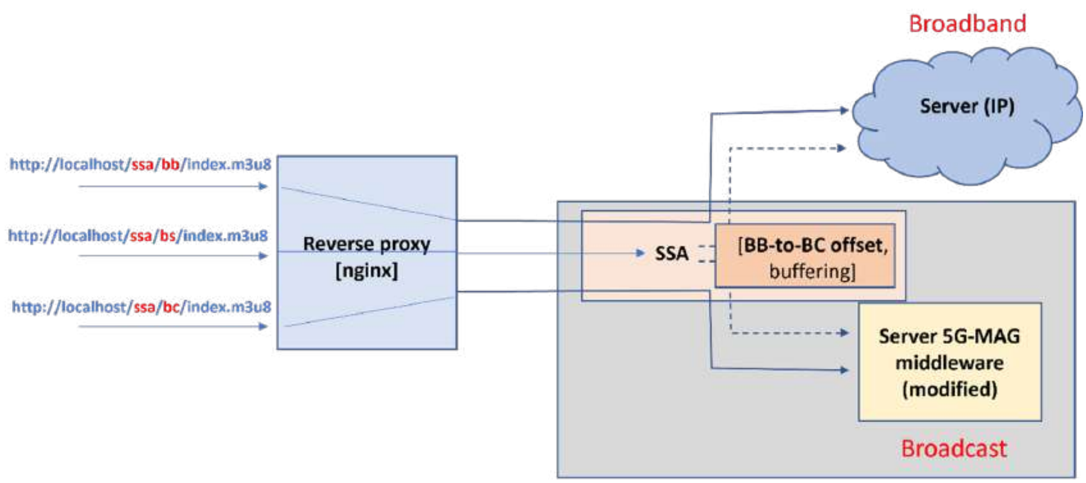


Figure 4.1: SSA channels

The BC source is provided by the Demodulator and MBMS client of the 5G-MAG RT, while the BB source is provided by a Content Delivery Network (CDN).

In the BS channel, which is the core of the application, a complete redesign of the client interface and the method of requesting and exchanging files with BC and BB servers has been undertaken to ensure the required robustness. The application performs a complete regeneration of index files and segment naming, which are then presented to the client application (the streaming player).

Within the BS channel, the client does not connect to or interact with the BB or BC servers in any way. Instead, it exclusively communicates with the SSA server, which presents the segment index files entirely renamed with the prefix "segment_config_n", where "n" corresponds to their sequence number. Every segment or index file requested by the client is then transmitted directly from the SSA server after appropriate processing of the original index and segment files. These original files are downloaded by SSA from the BB or BC servers, depending on the current state of the BS channel.

The states of the BS channel mapped within SSA include "BC" (tuned to the broadcast server), "BB" (connected to the broadband server), "BB2BC" (switching in progress from BB to BC), "BC2BB" (switching in progress from BC to BB), or "None" (neither of the two channels is active).

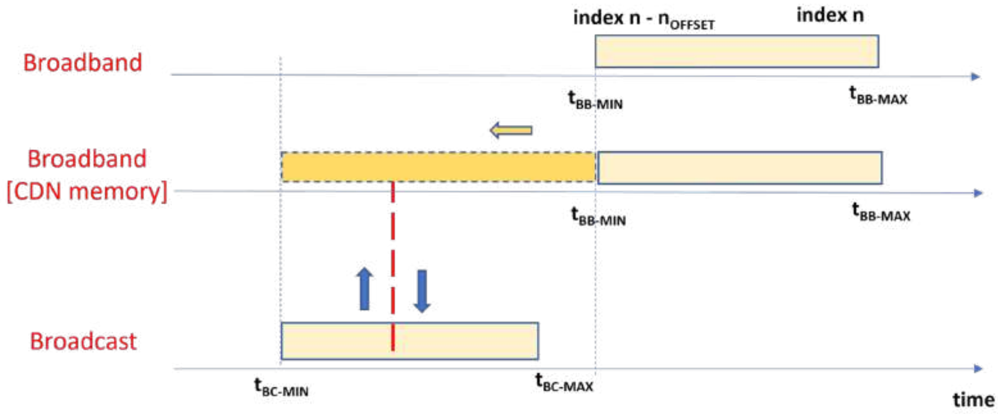
4.2. Channel synchronisation

It is essential to emphasize that, to enable seamless switching in the BS channel, the streaming is synchronized with the slower channel between BB and BC. This alignment is achieved by estimating, both at the application's launch and periodically thereafter, the relative delay expressed in the number of segments between the two servers. Subsequently, the segment indices are adjusted (delayed) accordingly when the BS channel downloads the streaming from the faster channel.

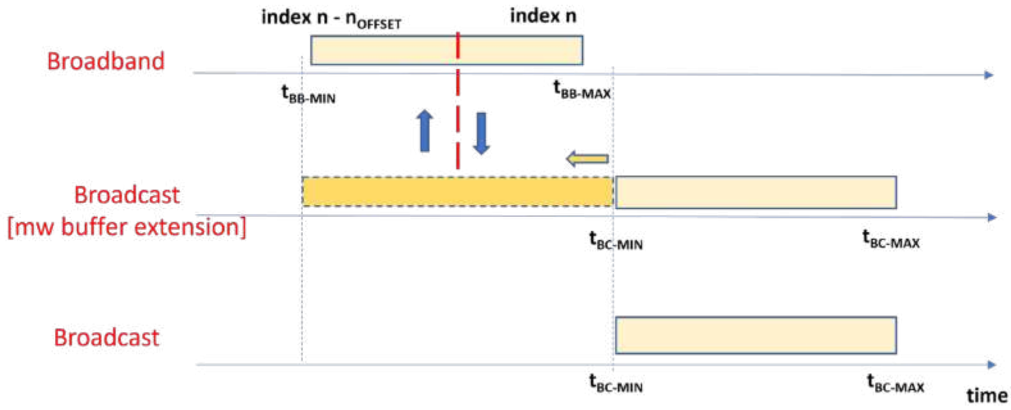
In this context, the symmetry of all functions between the BB and BC channels has been fully established, allowing for switching under any condition of mutual delay, whether it be the BB channel being ahead or behind the BC channel (Fig. 4.2):

- In the case of the BB channel being ahead, the application leverages the buffer (memory) of the CDN network, which is significantly larger than the typical delays observed between BB and BC (15 – 30 seconds).
- In the case of BC being ahead, the application utilizes the buffer of the Middleware.

This buffer size is configured through the "max_file_age" parameter within the 5G-MAG 5gmag-rt.conf configuration file, with a suitable size of 60 seconds.



(a) BB ahead of BC



(b) BC ahead of BB

Figure 4.2: Channel synchronisation

4.3. Processes

As outlined in Fig. 4.3, the SSA server comprises five primary processes that operate concurrently once the application is launched:

1. **"read_ssa_input_command" process:** this process interprets commands received from the terminal. These commands pertain to the status of the switching channel, enabling automatic switching with its parameters, and designating the source for the BS channel (BB or BC).

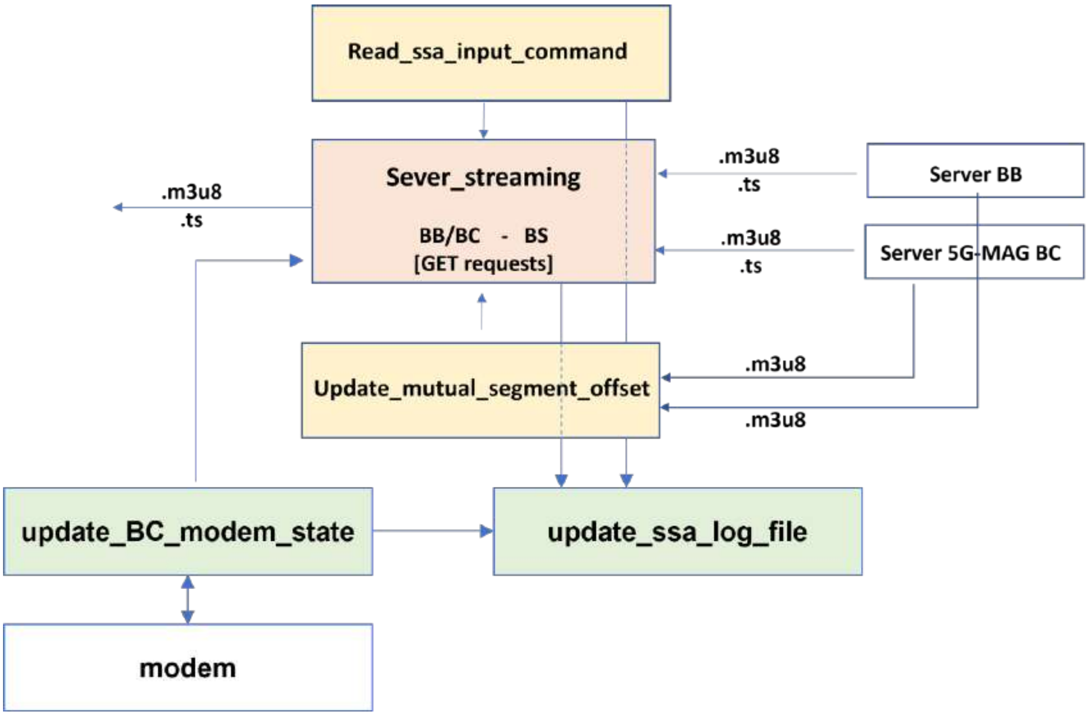


Figure 4.3: SSA core processes

2. **"update_mutual_segment_offset" process:** periodically, typically every 30 seconds, this process assesses the presence of both BB and BC channels. It requests and interprets their manifest files, calculates the offset, and consequently determines the relative delay between the two streams. This information is crucial for enabling (i) seamless switching, which compensates for the relative delay, and (ii) automatic switching in case the stream tuned to the BS channel becomes no longer active.

3. **"update_BC_modem_state" process:** this process retrieves the Signal-to-Noise Ratio (SNR) measurements from the BC channel's Demodulator when available, utilizing the provided Application Programming Interfaces (API). This SNR measurement is vital for guiding automatic switching decisions, such as switching from BC to BB when the SNR falls below a predefined threshold to maintain uninterrupted streaming or switching from BB to BC when the SNR surpasses the threshold to reduce broadband network traffic.

4. **"update_ssa_log_file" process:** this process is responsible for managing and updating log files, providing more comprehensive and customizable log functionality for the application. These features can be enabled or configured using the 'log_server' parameter within the 'server_ssa.ini' configuration file.

5. **"server_streaming" process:** responsible for managing video streaming requests across the three channels. While BB and BC channels are straightforward redirections to the original servers, the BS streaming is entirely regenerated by the application to appear as a new, independent source for the HLS client. Initially, the streaming is synchronized with the source having the highest delay to ensure seamless switching, with the other source buffered as needed.

4.4. SNR switching

The Signal-to-Noise Ratio (SNR) switching functionality has been implemented to achieve seamless automatic switching based on the measured SNR at the receiver (BC modem). The goal is to enable automatic switching when the SNR falls below a certain threshold (SNRT), which is determined by the modulation and coding scheme (MCS) used. When the SNR drops below SNRT minus a hysteresis value (SNRH, typically 2dB in our case), automatic switching to the BB channel is initiated if the source is available. Conversely, when the SNR rises above SNRT plus SNRH, the system triggers a switch back to the BC channel. The SNR reading occurs with requests made either to the server installed by the 5G-MAG rt-wui application or directly to the Modem, at a frequency indicated by the "update_BC_modem_period" parameter in the SNR configuration file (typically 1 second).

The SNR switching functionality is managed in two modes, implemented by the processes (1) "update_BC_modem_state" or (2) "update_BC_modem_state_switching_mng", which is an evolution of the first mode.

1. **Automatic switching:** automatic switching is governed by the "suspend_BC _modem" parameter, following this logic: BC2BB switching is activated when an SNR lower than (SNRT - SNRH) is detected, and at the same time, this automatic switching mode is deactivated for a duration of "suspend_BC_modem" seconds (typically 6-12 seconds). Suspension is introduced to ensure that the stay in the BC or BB state is not too short, regardless of the SNR evolution. This avoids a rapid switching of the state that would lead to instability.

2. **Window-based automatic switching:** automatic switching is controlled by both "suspend_BC_modem" and "offset_BC_modem" parameters (this mode is activated if "offset_BC_modem" $>$ 0, otherwise mode 1 is executed automatically). To enhance process stability, a window mechanism has been implemented.

   The window's position in time is determined by the "offset_BC_modem" delay (between the current SNR reading and its center), and it has an extension equal to "suspend_BC_modem", as shown in Fig. 4.4. This allows for delayed switching compared to the previous mode and minimal extension. The content of this SNR observation window is updated with each SNR reading event, ensuring it delineates a precise time interval.

This process more effectively compensates for the delay between a negative SNR event and its impact on streaming in the player. Moreover, it prevents rapid switching events; switching is activated only if the current window contains at least one negative SNR event (below SNRT - SNRH), and a return to the BC channel after an automatic BC2BB switch occurs only when the window exclusively contains positive SNR events (above SNRT + SNRH).

As shown in the Fig. 4.4, the current reading is taking place at the blue dashed bar but switching is activated or maintained (if already activated between BC and BB) due to the presence of sub-threshold SNRs in the observation window.

Additionally, the SSA server implements the segment switching functionality. When this mode is enabled (through the "enable_segment_switching" parameter in the configuration file), the SSA server can request a single segment from the BB or BC channel without performing an actual channel switch. This capability is useful in cases where the BB or BC servers do not respond promptly or return an error upon the initial segment request.

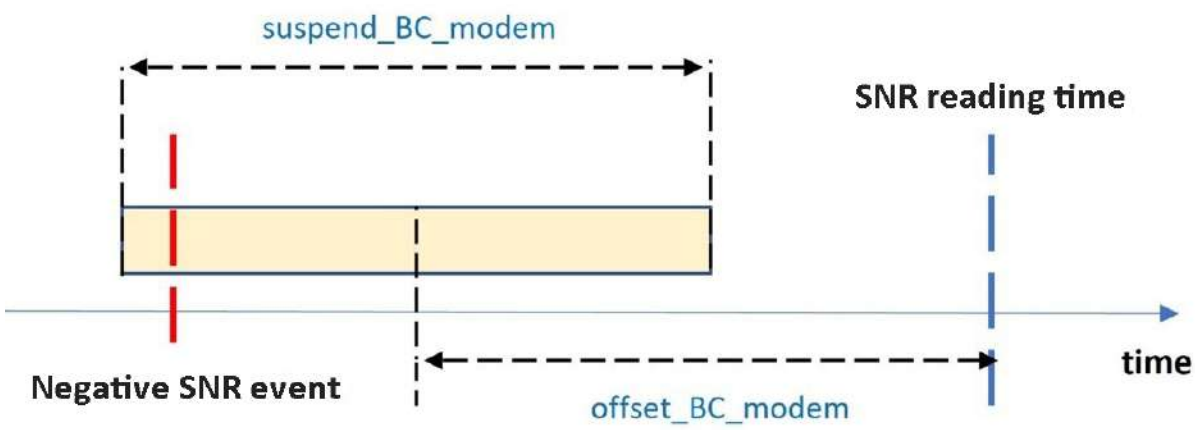


Figure 4.4: Window operation

5 | On the field measurements

Within the context of Auto Infotainment Content Consumption (AICC) use case (Section 1.1.3), the SSA has been field-tested. This involved gathering data to analyze its performance and understand its potential issues.

5.1. Context and experimental setup

The experimentation took place in Turin on July 13 2023, using the 5G transmitter of Torino Eremo, granted to Rai Way for the experimental period of the ministerial project. [59]

The objective was to verify the operation of the SSA on a moving car. For this reason, a route was chosen that was sufficiently distant from the transmitter and with the presence of skyscrapers disturbing the signal (Fig. 5.1).

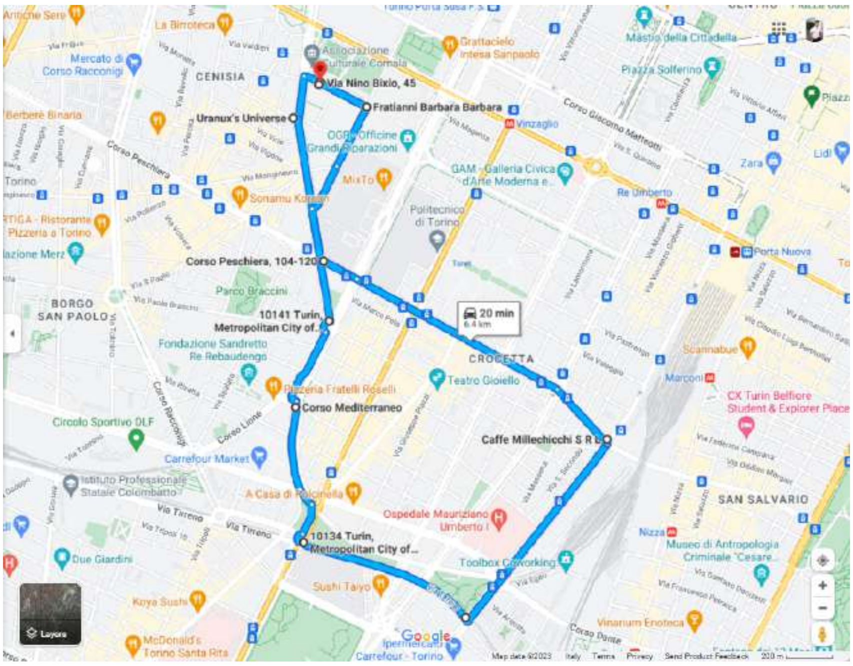


Figure 5.1: Route

The experimental setup includes a part concerning the reception of the media stream (broadcast/broadband) and a part concerning the recording of GPS data.

Media stream setup:

- Mobile antenna placed on the roof of a car, with the antenna amplifier switched off
- Ettus Universal Software Radio Peripherial (USRP) B210
- PC Lenovo Yoga Slim 7, 16GB RAM, AMD Ryzen 7 4700U processor
- Android smartphone with internet connection via 5G

The antenna was connected to the B210 which in turn transmitted the data to the PC. The latter was also connected to the internet via the Android smartphone.

Seamless Switching Application (SSA) was run on the PC. In order to function properly, the application needs both MBMS Modem and Middleware of 5G-MAG to run at the same time (Fig. 5.2).

GPS data recording setup:

- PC ThinkPad P52, 32GB RAM, Processore i7-8750H
- Geekstory VK-172 Gmouse USB GPS Glonass Module Dongle
- Two Android smartphones with Google Maps

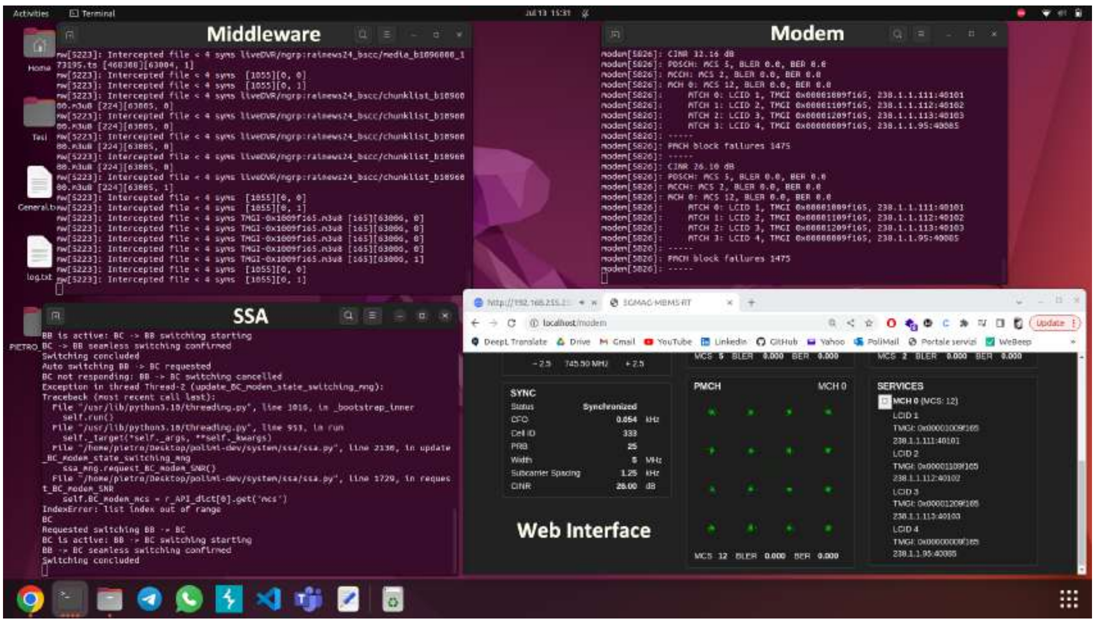
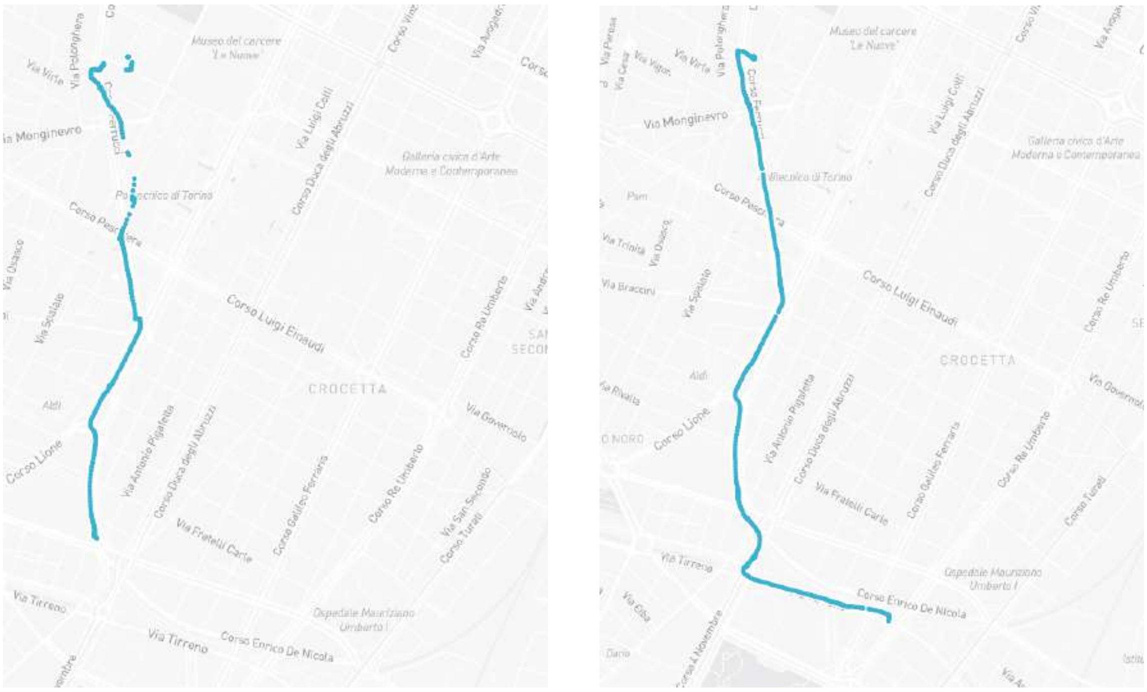


Figure 5.2: Running applications per media stream

The GPS dungle was connected to the PC and through a Python script data were saved locally. Due to a malfunction of the system for part of the route, it was necessary to use Google Maps data recorded by smartphones (Section 5.2.1).

5.2. Data collection and reconstruction

The collected data logs were subsequently filtered using custom-written parsing programs. Trying to correlate the GPS data with the SSA log data using timestamps, it became evident half of the positional data in both datasets had not been captured, as shown in Fig. 5.3.

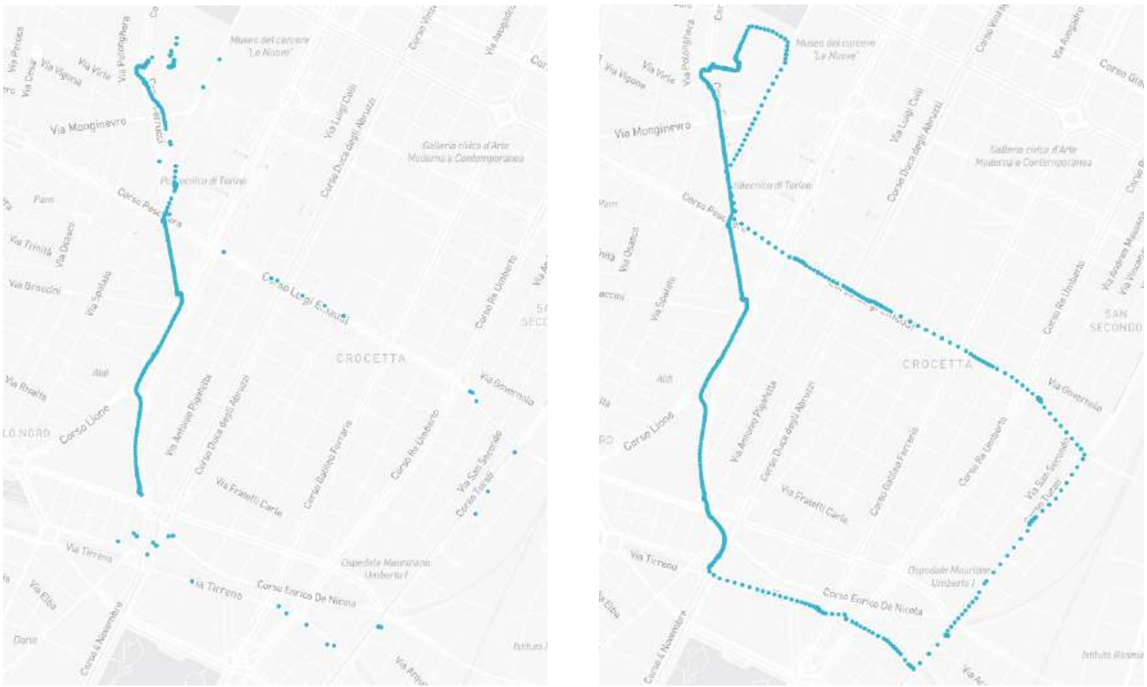


(a) Measurement 1 (b) Measurement 2

Figure 5.3: GPS original results

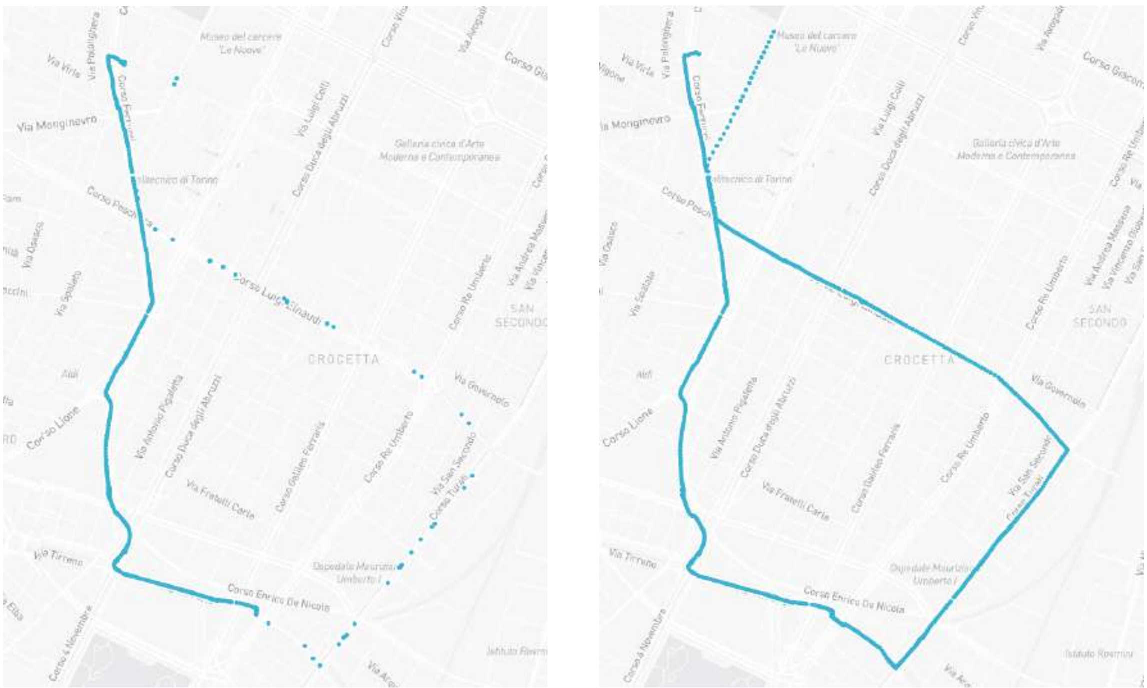
5.2.1. GPS reconstruction

Not having all the positional data of the route available, it was necessary to retrieve the missing data from Google Maps recorded by smartphones. The points obtained were then interpolated to find the best route estimate. The results for both measurements are shown in Figs. 5.4 and 5.5.



(a) Google Maps (b) Interpolation

Figure 5.4: GPS Measurement 1

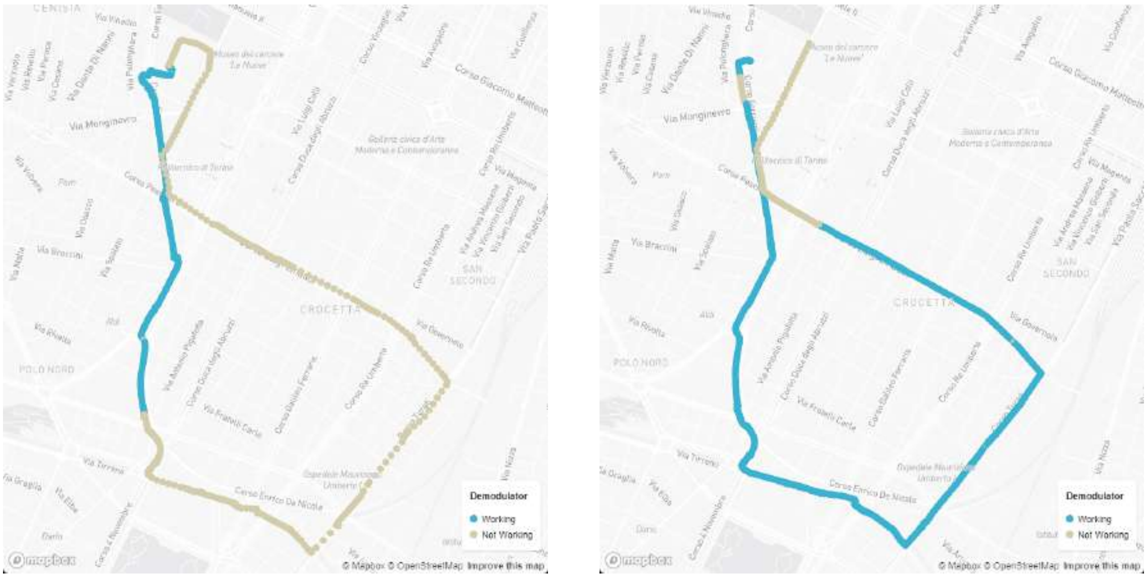


(a) Google Maps (b) Interpolation

Figure 5.5: GPS Measurement 2

5.2.2. Demodulator instability

After reconstructing the positional data, it became feasible to overlay it with the SSA log data. Plotting this information on a map (Fig. 5.6) revealed instances where the Demodulator failed to provide a valid Signal-to-Noise Ratio (SNR). Errors often block the execution of the latter, making the work of the MBMS Client not possible.



(a) Measurement 1 [60]

(b) Measurement 2 [61]

Figure 5.6: Demodulator operation

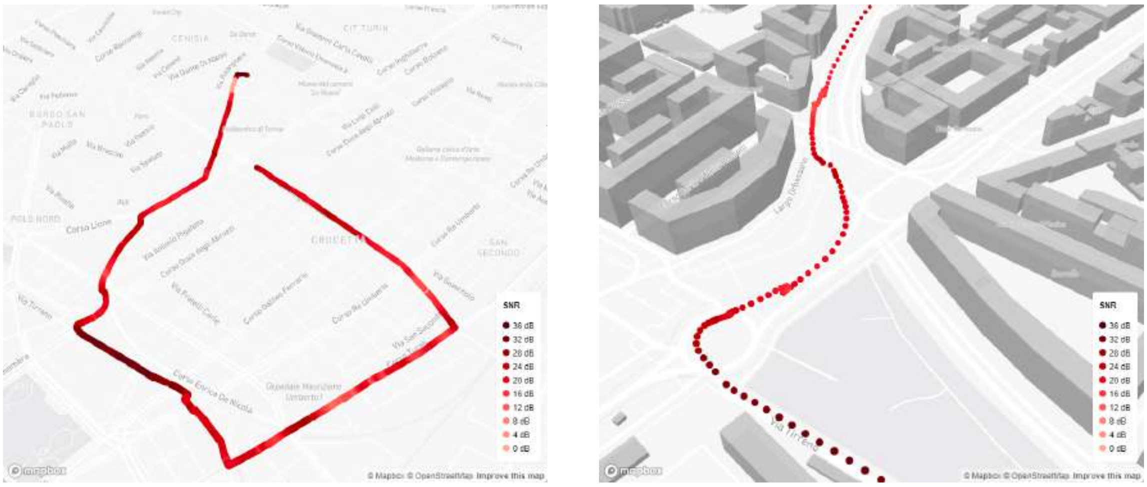
Unfortunately, this information was only evident in post analysis of the data and necessarily caused the exclusion of the Measurement 1, as it took place almost entirely in broadband.

5.3. Results and data analysis

5.3.1. SNR-related results

The first step taken was to analyse the SNR-related results by means of a 3D heat map and try to hypothesise possible correlations between signal strength and position in the path, as shown in Fig. 5.7.

An initial analysis was conducted to examine a potential correlation between SNR and speed. However, no such correlation was found, affirming the reliability of 5G connectivity even during motion [63].



(a) Whole route (b) Route between 3D buildings

Figure 5.7: SNR heat map [62]

The analysis shifts to finding a correlation between SNR and signal interference, with Matlab's Line-of-Sight (LoS) function [64] automatically calculating the points that have a direct connection to the transmitter (Fig. 5.8).

The results obtained are logical: points with direct line of sight have a higher SNR (Fig. 5.9). Upon closer inspection of the acquired SNR value distribution, it becomes apparent that instances with LoS exhibit a notably higher average SNR. Intriguingly, their distribution, though, is characterized by less uniformity (Figs. 5.10 and 5.11).

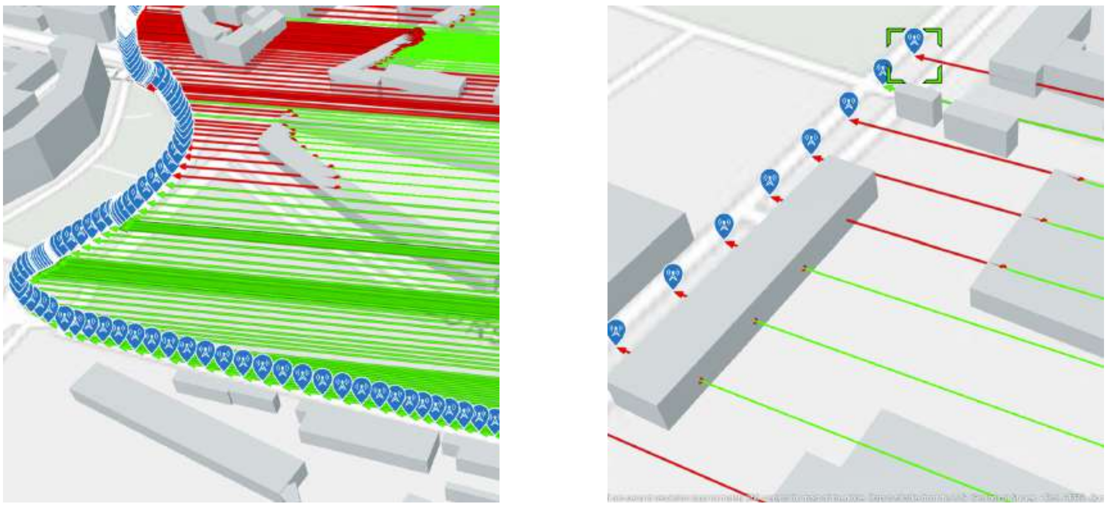


Figure 5.8: Matlab's LoS function [65]

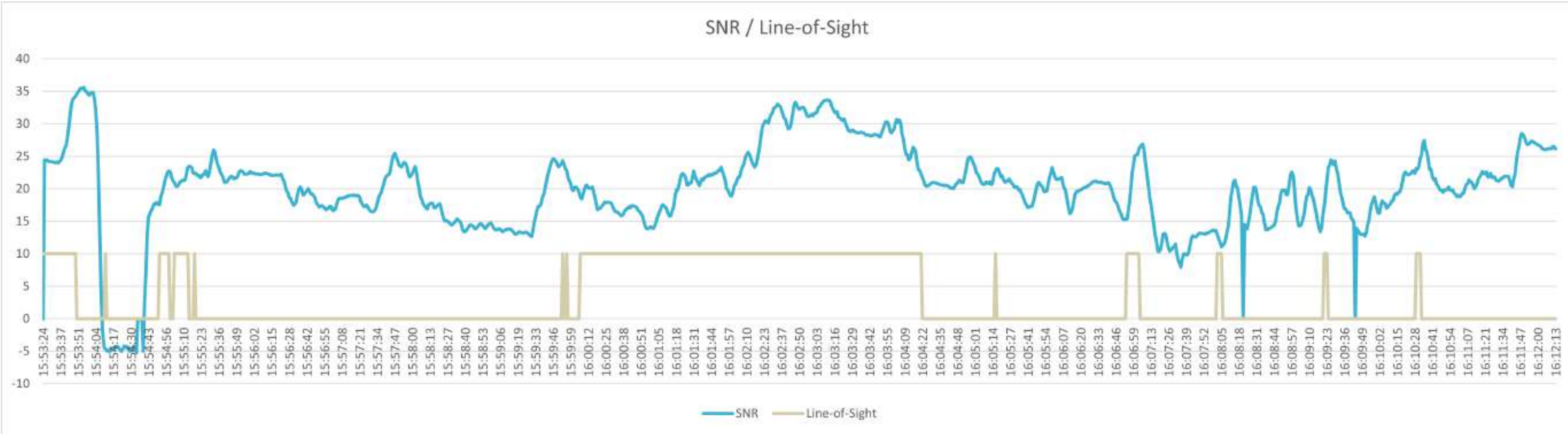


Figure 5.9: SNR / Line-of-Sight

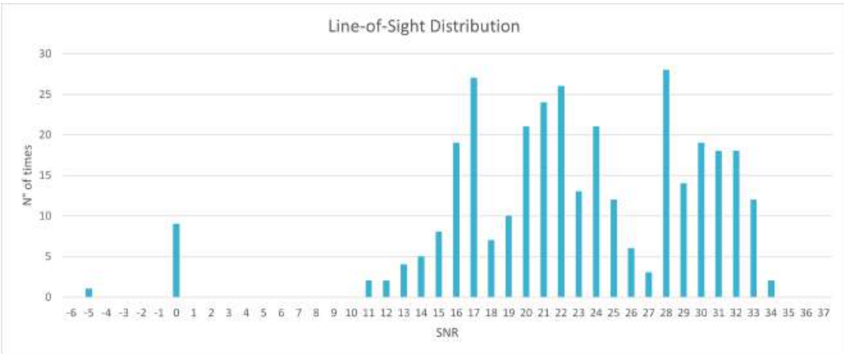


Figure 5.10: Line-of-Sight Distribution

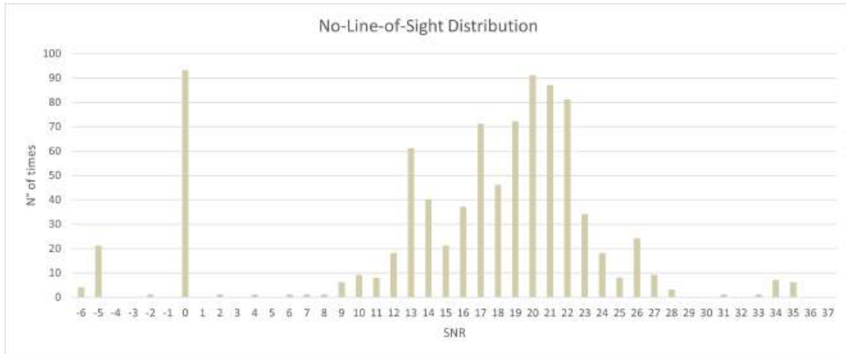


Figure 5.11: No-Line-of-Sight Distribution

This unexpected pattern might be attributed to the pivotal roles that distance and the propagation environment play in influencing these outcomes. The measurements collected are few and scattered in different locations, to reach more precise conclusions we would need many more measurements in more selected areas but this was not the primary aim of the experimentation.

5.3.2. Player miss analysis

An essential factor to take into account is the fluidity of the video in the player. The SSA log enables the tracking of requested chunks and their corresponding timestamps, allowing the detection of instances referred to as 'miss' moments. These moments occur when specific chunk is skipped, which can be identified by being numbered in an ascending manner; or when a gap of more than 3 seconds, that is the duration of a single chunk, occurs between consecutive chunks.

Looking for a correlation between miss moments and other measurement parameters, it can be seen in Fig. 5.12 that there is a direct relationship with SNR values, although not a very clear one. Continuing the analysis, a much clearer correlation was found between the misses and the moments of switch from broadcast (BC) to broadband (BB) of the SSA (Fig. 5.13).

Figure 5.12: SNR / Miss

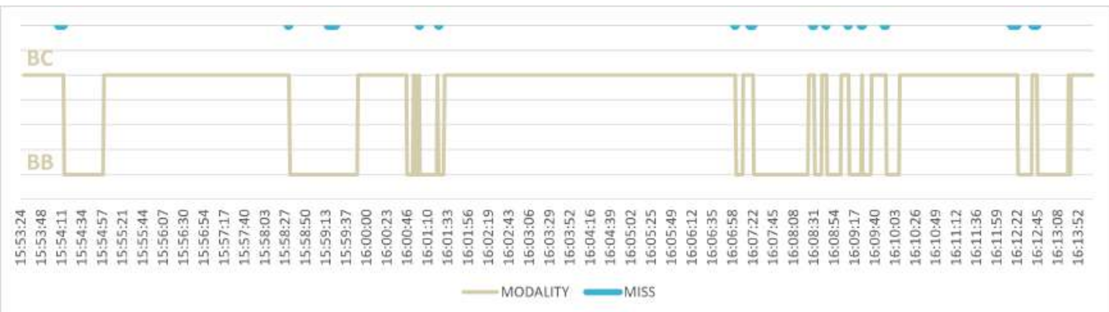


Figure 5.13: Modality / Miss

5.4. Emulator and improved parameterization

After establishing a correlation between "misses" and the transition from broadcast to broadband, the focus turned to analyzing the functionality of the SSA. This analysis aimed to identify potential enhancements that could be implemented to improve its performance.

5.4.1. Window

One of the primary parameters that requires careful monitoring is the SSA window (Section 4.4). Window time holds significant importance due to its potential to exceed the optimal size. When this occurs, it has the risk of affecting the fluidity of the video. Moreover, this could lead to the conservation of corrupted chunks associated with SNR below the threshold, consequently resulting in "misses" for the player.

5.4.2. Emulator

An emulator for the 5G Broadcast transmitter was developed to assess the performance of the SSA as the window size was altered.

Its functionality involves receiving a broadband stream, introducing a delay, and inputting an SNR value sourced from a file within the directory (Fig. 5.14). By utilizing the list of SNR values collected during experimentation, a precise and accurate simulation can be conducted. To enhance the realism of transitions and to track "misses" effectively, when an SNR falls below the threshold, the corresponding chunk is deliberately corrupted, and this approximately corresponding to the subsequent 2 chunk as shown in Fig. 5.15. The delay is due to the time the chunk takes to travel from the Demodulator, where its SNR is read, to the MBMS Client, from which the chunk's content is requested.

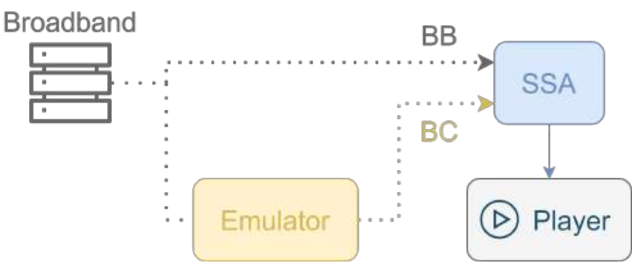


Figure 5.14: System flow

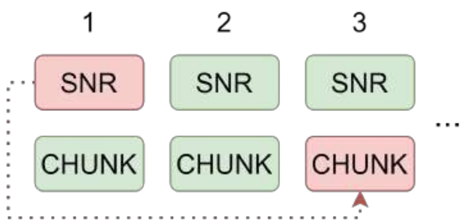


Figure 5.15: SNR-chunk

5.4.3. Improved parameterization

Exploiting the functionality of the emulator and trying to simulate the experiment with the same parameters yielded very similar results. This strongly suggests that the occurrences of 'misses' by the player were indeed connected to this specific parameter.

Through the execution of multiple simulations and the gradual reduction of the window size, a clear correlation emerged indicating a direct link to the count of "misses", until reaching approximately 6 seconds. At this point, the video's smoothness exhibited significant stability, and this outcome aligns logically with the previously mentioned information since the emulator introduces a delay in chunk corruption by two segments, each spanning a precise duration of 3 seconds.

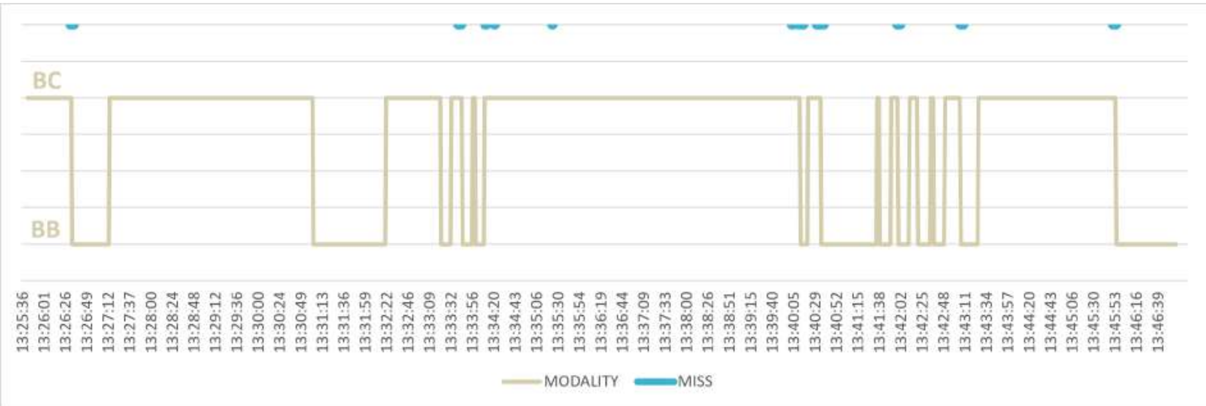


Figure 5.16: Window simulation 10s

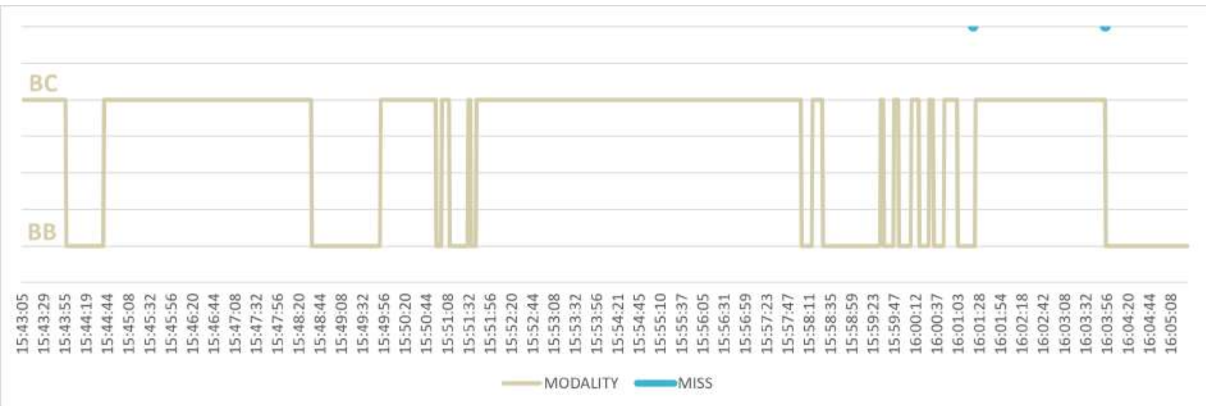


Figure 5.17: Window simulation 6s

6 | Conclusions

This project has encompassed a wide range of objectives and initiatives. It has successfully implemented a 5G Broadcast solution in alignment with the 3GPP Rel.14 standard, improving the open source solution already developed by the 5G Media Action Group (5G-MAG), and harnessed the capabilities of 5G Private Network technology at designated Turin locations to contribute produced media content.

During the evolution of the project, meticulously customised use cases were presented and explored to meet the unique requirements of the experimental territory. This endeavor has been characterized by the seamless integration of cutting-edge technologies, including Content Delivery Networks (CDN) for the efficient processing and distribution of media content, the immersive potential of VR360° technology for video production, and the capabilities of 5G Broadcast technology for delivering audiovisual content to mobile devices.

The active involvement of the Politecnico di Milano in the project has significantly contributed to its overall success, particularly in the development of the Seamless Switching Application (SSA), designed to receive both 5G Broadcast and broadband audiovisual signals, facilitating their collaboration to ensure a consistently high streaming quality. That has undergone a progressive evolution, starting from its basic functionality and gradually expanding its various modes and parameters to cater to different purposes.

Subsequent work was also carried out to optimise the SSA parameters in the field, which yielded valuable results for further analysis and considerations.

6.1. Parameterization analysis

When analysing the player's fluidity during field tests (Section 5.4.3), the results were in line with expectations: a significant reduction in player 'miss' events was achieved due to an improved window system. Miss' moments occur when specific portions of video are skipped or when there is a gap of more than 3 seconds between consecutive portions, while the system's window mechanism is used to effectively compensate for the delay between a negative Signal-to-Noise Ratio (SNR) event and its impact on streaming in the player.

During the simulation, a static delay of 2 chunks was enforced, reflecting the average observed during field experimentation. However, it's important to note that this delay is not actually fixed; rather, it's influenced by numerous factors, including the hardware on which the receiver operates, chunk duration, number of MBMS Clients connected to the Demodulator.

Another noteworthy observation pertains to the clear distinction between the excellent performance consistently achieved when video streaming utilizes 5G Broadcast above the established SNR threshold, and the occurrence of occasional "miss" events when the SNR declines and the system switches to broadband. This might happen in areas where signal reception is significantly disturbed. It's still valuable to be aware of this possibility, as it allows for potential solutions such as deploying signal repeaters for broadcast or broadband signal to mitigate this issue.

6.2. Future directions

The application developed during this project, along with the improved parameter results, paves the way for numerous potential future uses and advancements.

An intriguing avenue for exploration could involve the development of a geographical SNR mapping system to assist mobile receivers. In the specific context of automotive applications, utilizing a car's GPS, the SSA could proactively prepare for switching by anticipating regions with weak 5G Broadcast signals into which the vehicle is entering.

Another intriguing advancement could involve designing a portable receiver that encompasses all the essential elements for receiving broadcasted content. This would essentially offer an end user a self-contained tool capable of carrying and operating independently, without relying on an internet connection, for accessing multimedia content.

Glossary

3GPP 3rd Generation Partnership Project. 1–4, 12, 18, 19, 61

5G-MAG 5G Media Action Group. 9, 30, 31, 33, 35, 39, 44, 46, 47, 52, 61

A/V Audio/Video. 5, 6, 8

ABR Adaptive-BitRate. 5, 24, 25

ADCs Analog-to-Digital Converters. 35

AICC Auto Infotainment Content Consumption. 51

ALC Asynchronous Layered Coding. 37–42

AMF Core Access and Mobility Management Function. 14, 15, 18

API Application Programming Interfaces. 48

AR Augmented Reality. 1

BER Bit Error Rate. 37

BM-SC Broadcast Multicast Service Centre. 4–6

BNOs Broadcast Network Operators. 1

BSCC 5G Broadcast Service & Control Centre. 4, 5

CCCH Common Control Channel. 18

CCI Congestion Control Information. 43

CDN Content Delivery Network. 1–6, 37, 46

CFI Continuous Flow Intersection. 36

CMAF Common Media Application Format. 28

CRC Cyclic Redundancy Check. 16

CSI Channel State Information. 16

CU Centralized Unit. 37

DAB Digital Audio Broadcasting. 4

DACs Digital-to-Analog Converters. 35

DASH Dynamic Adaptive Streaming over HTTP. 4, 5, 24, 26–28, 30, 33, 37, 38

DCCH Dedicated Control Channel. 18

DCI Downlink Control Indicator. 36

DTT Digital Terrestrial Television. 2, 4

DU Distributed Unit. 37

FDT File Delivery Table. 40, 41

FEC Forward Error Correction. 40, 42

FFT Fast Fourier Transform. 37

FLUTE File Delivery over Unidirectional Transport. 4, 5, 33, 37–40

gNB gNodeB. 12–16

GOP Group of Pictures. 6

GPS Global Positioning System. 23, 52, 53

HARQ Hybrid Automatic Repeat Request. 16, 17

HEVC High Efficiency Video Coding. 9

HLS HTTP Live Streaming. 4, 5, 8, 24–28, 30, 33, 37, 38, 45, 49

HMI Human Machine Interface. 7

HPHT High Power High Tower. 6, 9

I/Q In-Phase and Quadrature. 35

ICT Information and Communications Technology. 31

IIoT Industrial Internet of Things. 23

IoT Internet of Things. 11, 19, 20, 22, 23

IP Internet Protocol. 4

IPTV Internet Protocol Television. 2

LCT Layered Coding Transport. 38, 39, 42, 43

LL-HLS Low-Latency HLS. 26, 28

LoS Line-of-Sight. 56

LTE Long-Term Evolution. 12, 14, 23, 33

MAC Medium Access Control. 16–18

MBMS Multimedia Broadcast/Multicast Service. 31, 33, 35–38, 44, 46, 52, 55, 59, 62

MBMS GW Multimedia Broadcast Multicast Service Gateway. 4, 5

MBR Multi-BitRate. 24, 25

MCCH Multicast Control Channel. 36

MEC Multi-Access Edge Computing. 19

MIB Master Information Block. 36

MIMO Multiple-Input Multiple-Output. 21

MME Mobility Management Entity. 14

MNOs Mobile Network Operators. 1

MPD Media Presentation Description. 26, 27

MPEG Moving Picture Experts Group. 5, 26–28

MPLS-TE Multiprotocol Label Switching - Traffic Engineering. 4

MTCH Multicast Traffic Channel. 36, 37

NAS Non-Access Stratum. 18

NFV Network Function Virtualization. 19, 20

ng-eNB Next Generation eNodeB. 13

NG-RAN Next-Generation Radio Access Network. 14

NR New Radio. 13, 16, 18, 19

O-RAN Open Radio Access Network. 20, 37

OFDM Orthogonal Frequency-Division Multiplexing. 36

OTA Over-the-Air. 4

OTT Over The Top. 2, 5

PCF Policy Control Function. 14, 15

PDCP Packet Data Convergence Protocol. 17

PDU Protocol Data Unit. 13–15, 17, 18

PRB Physical Resource Block. 37

QoS Quality of Service. 13, 15, 17

RAI Radiotelevisione Italiana. 35

RAN Radio Access Networks. 12–14, 19, 20, 33, 37

RATS Radio Access Technologies. 12, 13

RF Radio Frequency. 35

RFID Radio Frequency Identification. 23

RLC Radio Link Control. 17, 18

RRC Radio Resource Control. 16, 18

RT Reference Tools. 31, 33, 35, 44, 46

SDAP Service Data Adaptation Protocol. 17

SDL Supplemental Downlink. 6

SDR Software-Defined Radio. 33, 35, 36

SIB System Information Block. 36

SMF Session Management Function. 14, 15, 18

SNR Signal-to-Noise Ratio. 48–50, 55, 56, 58, 59, 62

SRB Signalling Radio Bearers. 18

SSA Seamless Switching Application. 3, 5, 9, 45–47, 50–53, 55, 58, 59, 61, 62

TOI Transmission Object Identifier. 39–41, 43

TSI Transport Session Identifier. 39, 43

UDM Unified Data Management. 15

UDP User Datagram Protocol. 37

UE User Equipment. 12, 15, 16, 18

UHF Ultra High Frequency. 19

UPF User Plane Function. 13–15

URI Uniform Resource Identifier. 40

USRP Universal Software Radio Peripherial. 35, 52

V2X Vehicle-to-Everything. 1

VR Virtual Reality. 1, 6, 8, 9

vRAN Virtual RAN. 12

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