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"Development of Software Defined Radio Applications for Audiovisual Content Distribution Using Mobile and Broadcast Networks"

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Abstract

The rapid growth in mobile user equipment(UE)and advanced applications has led to a significant rise in the demand for data traffic.In general,reception of data contents in high UE mobility scenarios could be a challenging task due to the possible interference effect that can degrade signal quality and impact receiver's performance. The present thesis focuses on optimizing a 5G broadcast receiver for the efficient and reliable delivery of audiovisual content in mobile and high-mobility environments using Software Defined Radio (SDR).

To address these challenges, this research introduces novel optimizations to Log-Likelihood Ratio (LLR) computations and dynamic noise thresholds, making signal processing more adaptive and robust. These optimizations were rigorously tested through a combination of laboratory simulations and real-world trials conducted in high-speed vehicular environments.

The trials demonstrated a 10 dB improvement in the Carrier-to-Noise (C/N) ratio under specific condition, validating the significant potential of integrating SDR into 5G broadcast systems, especially in challenging, high-mobility environments.

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Introduction

The broadcasting industry is undergoing significant transformations driven by advancements in communication technologies. These changes have introduced new user expectations, requiring broadcasters to adapt quickly to maintain their market positions. Traditionally, broadcasters provided linear TV and radio programs with limited user interaction. However, the advent of the internet and supporting technologies has revolutionized the industry, enabling broadcasters to distribute their content to a wide range of digital media platforms.

Technological advancements have fueled the rise of on-demand services, shifting media consumption patterns. While linear services remain important, their growth has stabilized or declined in certain regions. This trend is particularly evident among younger audiences more oriented towards on-demand content via personal devices like smartphones and tablets. Additionally, the increasing connectivity of vehicles presents new opportunities for media consumption on the go, making it crucial for broadcasters to target these emerging markets.[1]

To address these changes, broadcasters are adopting a new model consumption centered around the concept of "anything, anywhere, anytime, on any device." This approach aims to deliver personalized services that seamlessly combine live broadcasts and on-demand content, providing an improved and more immersive user experience.[1]

With the aim of providing the services described above while serving the largest number of end-users, media companies have started to look at the opportunities offered by the 5G technology. Indeed, the new functionalities introduced in the broadcast/multicast profile of 3GPP Rel 14-16[2] also known as "5G Broadcast" could represent a very promising opportunity to address the technical and business challenges of the entire media sector since they allow in principle,a close synergy between network operators and content provider in reaching large audiences while using network resource in more efficient way.[3]

The broadcast profile defined in 3GPP Rel-14 and Rel-16 standards support large-scale TV content delivery directly to personal consumer devices, setting a new challenge in the media landscape. These advancements facilitate the seamless integration of broadcast and broadband networks, enhancing network resource utilization, reducing CDN costs, and creating new market opportunities across the value chain in service provision and content production. Additionally, 5G Broadcast aim to alleviate the traffic load on traditional mobile networks and support edge caches to store popular content, ensuring efficient delivery and minimizing network congestion.[3]

The objective of the research work reported in the present thesis is aimed at the developing of SDR (Software Defined Radio) applications for audiovisual content distribution using mobile and broadcast networks.

In particular ,the thesis work is organized as follows:

- Chapter 1 provides an overview of the increasing demand from users for high-quality audiovisual content , highlighting the advancements in 3GPP technologies, particularly FeMBMS, which is designed to overcome these limitations. Chapter 2 explores the integration of 5G Broadcast and Broadband technologies, emphasizing how this integration addresses the growing need for efficient media service delivery. This chapter also discusses the network-level and service-level cooperation strategies, and show the significant role played by the 5G Media Action Group [4]. Chapter 3 is meticulously detailed, describing the setup, simulation scenarios, and data collection methods used to improve 5G broadcast capabilities through Software Defined Radio (SDR). This Chapter also tackles the complex challenges of channel estimation in dynamic environments and presents the solutions implemented to improve signal reception.Chapter 4, presents the performance metrics derived from these experiments, providing a thorough data analysis and comparing these results with previous research to highlight the technological improvements achieved. Finally, Chapter 5 summarizes the research findings, discussing their practical implications for the broadcasting industry and academic research,suggesting areas for future investigation.

Chapter 1

Specifications and New Features in 3GPP

1.1 Introduction

The demand for high-quality audiovisual content is growing swiftly, placing significant pressure on existing mobile network infrastructures.Traditional unicast transmission methods, where separate data streams are sent to each user, fail to efficiently scale during high-traffic events like live sports broadcasts or popular show releases. This inefficiency results in network congestion and degraded user experiences, particularly during peak usage times.

To address these challenges, 5G broadcast technologies optimize content deliver and reduce the strain on mobile networks. Key among these are Further Evolved Multimedia Broadcast Multicast Service (FeMBMS) standard[2], which broadcast a single content stream to multiple users simultaneously. This approach enhances spectrum efficiency and reduces overall network load, allowing better delivering high-demand audiovisual content to large audiences.

This chapter explores the specifications and new features introduced in 3GPP, FeMBMS standard. This technology objectives to revolutionize mobile broadcasting by addressing the limitations of traditional unicast transmissions, promising a more reliable and efficient system for audiovisual content distribution.

1.2 Key Areas of Interest for 5G Broadcast to Mobile Devices

As mobile data traffic continues to grow exponentially, network operators face increasing challenges in meeting the demand for high-quality media delivery. According to the Ericsson Mobility Report [5], global mobile data traffic is projected to reach 313 exabytes per month by 2029, with smartphones alone generating approximately 95% of this traffic. This surge in data consumption, driven by the rise of video streaming and other bandwidth-intensive applications, underscores the need for more efficient spectrum utilization and advanced transmission technologies.

To address this growing demand, in 3GPP Releases 14 and 16, provide new capabilities for large-scale content delivery directly to consumer devices. The following sections outline the key areas where 5G broadcast technologies are making significant advancements:

1.2.1 Efficient Spectrum Usage

5G broadcast leverages multicast capabilities to deliver content to multiple users simultaneously, which significantly reduces network load compared to traditional unicast solutions. This efficiency is especially important during high-demand events, such as live sports broadcasts, where millions of users consume the same content simultaneously. In 2023, 5G accounted for around 25% of mobile data traffic, a figure projected to increase to approximately 75% by 2029[5]. The ability to broadcast a single stream to multiple users simultaneously optimizes spectrum usage, reduces network congestion, and improves the overall efficiency of mobile networks

1.2.2 Enhanced Coverage and Accessibility

5G broadcast aims to provide reliable service across diverse environments, including urban, suburban, and rural areas. In the next few years, global 5G population coverage outside mainland China had reached about 40% and is projected to increase to approximately 80% by 2029[5]. 5G broadcast addresses the challenges of coverage in deep urban zones and fringe areas, ensuring uninterrupted service through seamless switching between broadcast and broadband networks.

1.2.3 Integration with Existing Infrastructure

The integration of 5G broadcast with existing broadband networks offers significant advantages in resource utilization and cost reduction. By combining broadcast capabilities with Content Delivery Networks (CDNs), media companies can distribute content more efficiently, reducing the strain on CDNs and lowering costs associated with content delivery. This dual-distribution strategy enables broadcasters to deliver high-quality content to a larger audience while optimizing network resources. This integration is crucial for expanding content reach and improving user experiences.[3]

1.2.4 Market Opportunities and Business Models

The advancements in 5G broadcast technologies are unlocking new market opportunities for broadcasters and content creators. The efficient distribution of ultra-high-definition content, along with immersive formats such as Virtual Reality (VR) and Augmented Reality (AR), is significantly enhancing viewer engagement. These technologies enable broadcasters to develop new business models centered around personalized content delivery and interactive services. With the global 5G subscription base expected to reach close to 5.6 billion by 2029[5], broadcasters have the opportunity to capitalize on emerging trends and create tailored content experiences that cater to individual viewer preferences.

1.3 Offloading Traffic and Powering Edge Caches

The integration of 5G Broadcast technologies marks a significant evolution in network management, particularly through the introduction of traffic offloading and the strategic use of edge caches. These developments are crucial in addressing the increasing demands for high-bandwidth and low-latency Internet services, which are particularly pressing in densely populated urban settings.

1.3.1 Traffic Offloading Strategies

The concept of traffic offloading is pivotal in managing network loads effectively. By shifting substantial video traffic loads from conventional broadband networks to 5G Broadcast channels, the network can manage peak times more efficiently. This offloading is vital during high-demand events such as live broadcasts of major sports or large-scale concerts. The use of 5G Broadcast for offloading not only mitigates network congestion but also preserves bandwidth for other critical communications, thereby enhancing the overall network stability and performance.

1.3.2 Impact on 5G Broadcast

In 5G networks, traffic offloading and edge caching are integral for enabling efficient and reliable media delivery, especially during peak demand periods. These strategies allow networks to scale more effectively, reducing bottlenecks and ensuring continuous service.

1.4 The Role of Software Defined Radio in 5G Broadcast

As the 5G landscape evolves with frequent updates to standards, SDR offers the ability to update radio functions via software, rather than requiring costly hardware modifications.[6]

SDR enables broadcasters to simulate real-world conditions and optimize signal processing without the need for commercial 5G broadcast receivers, which are not yet widely available. This makes SDR essential for testing and refining 5G broadcasting protocols, allowing for rapid prototype development[7] and more accurate system tuning.

One of the major advantages of SDR is its support for advanced signal processing techniques such as dynamic channel estimation and adaptive error correction. These capabilities are critical in 5G environments, where challenges such as multipath fading, Doppler shifts, and signal degradation—especially in high-mobility environments—must be mitigated[6]. Open-source platforms like srsRAN [8]and OpenAirInterface[9] facilitate extensive experimentation, further optimizing the performance of 5G broadcast systems.

Additionally, SDR is highly adaptable to emerging technologies, such as artificial intelligence (AI), which allows it to dynamically adjust signal processing in real-time based on fluctuating network conditions[10]. This flexibility ensures that broadcasters can deliver high-quality, low-latency content even in challenging environments like urban centers or when delivering to moving vehicles.

Despite its current limitations in large-scale deployment due to cost and complexity, SDR remains invaluable for testing and refining 5G technologies. Its flexibility bridges the gap between evolving 5G standards and practical applications, ensuring that broadcasters can keep pace with technological advancements. In summary, SDR's adaptability and pivotal role in signal processing make it a cornerstone of future 5G broadcast development.

1.5 Enhanced Features in FeMBMS Release 14 and Subsequent Advancements in Release 16

FeMBMS introduced in 3GPP Release 14, represents a pivotal advancement in mobile broadcasting technology. This section details the key technical enhancements in FeMBMS Release 14, which were further refined in Release 16. These enhancements collectively facilitate a more scalable and efficient approach to media delivery. Key features include the introduction of a free-to-air and receive-only mode, extended cyclic prefixes, and robust cell acquisition sub frames, among others[11].

1.5.1 Free-to-air and Receive-only Mode

One of the most important features in FeMBMS is the free-to-air and receive-only mode, which allows devices to receive broadcast content without requiring a SIM card or a contractual agreement. ct with a mobile network operator. This feature significantly broadens accessibility and simplifies content distribution to mass audiences[11].

1.5.2 Dedication of Radio Resources

Release 14 allows for the dedication of 100% of the available radio resources to broadcasting in standalone mode, a significant enhancement over the previous limitation of 60%, enabling more efficient spectrum and network resource usage.[11]

1.5.3 Extended Cyclic Prefix(CP)

Extended Cyclic Prefix (CP): The implementation of an extended cyclic prefix of 200 microseconds allows to cover Inter Site Distances (ISD) up to approximately 60 km within a Single Frequency Network (SFN) framework. This extension significantly enhances spectrum efficiency, achieving up to 4.9 bit/s/Hz when utilizing 256-QAM modulation, excluding guard bands[11].

1.5.4 Cyclic Prefix for High Mobility

A 100-microsecond cyclic prefix has been introduced in REL 16 to accommodate high mobility scenarios, such as broadcasting to moving vehicles at speeds up to 250 km/h, enhancing the reliability of signal reception under high-speed conditions[12].

1.5.5 Robust Cell Acquisition Subframe (CAS)

Release 16 has also strengthened the cell acquisition subframe (CAS), essential for reliable signal acquisition and synchronization across the network, further bolstering the broadcast system's robustness and effectiveness.[12][13]

The advancements in 3GPP Releases 14 through 16 have brought significant improvements in mobile broadcasting, particularly through innovations like Receive-Only Mode (ROM) in Release 14 and enhanced support for high-mobility in Release 16. To provide a comprehensive overview, the following figure illustrates the key milestones in 3GPP releases, from Release 8 to Release 16, showcasing the evolution of LTE Broadcast and 5G Broadcast technologies.[14][12]

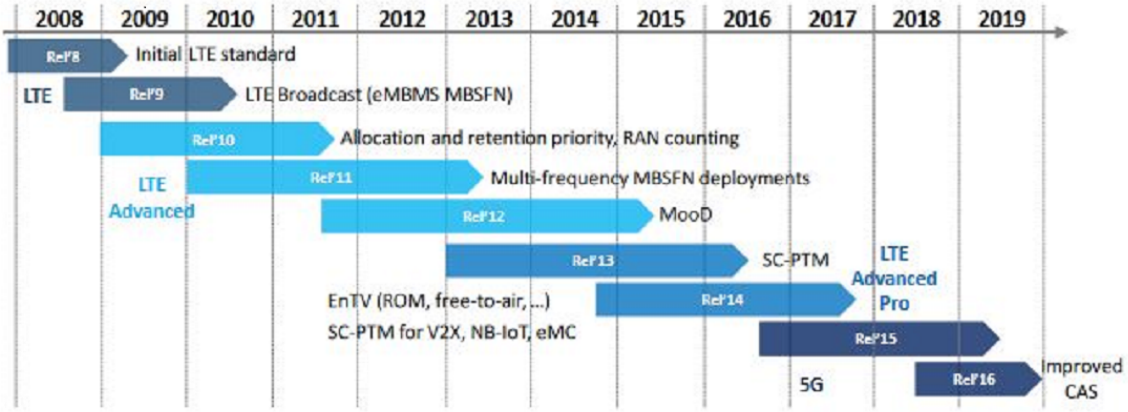


Figure 1.1: Timeline of 3GPP Releases from Release 8 to Release 16, showcasing key advancements in LTE Broadcast and 5G Broadcast technologies.[14]

As shown in the timeline(Figure 1.1), each 3GPP release introduced new features aimed at improving broadcast systems, enhancing the efficiency and reliability of content distribution across large areas and high-mobility environments. These technical advancements lay the foundation for the integration of broadcast and broadband systems, a topic that will be explored in the next section on deployment scenarios for 5G Broadcast systems.

1.6 Deployment Scenarios For Coexistance OF Existing And Future Terrestrial Broadcast Service With 5G

1.6.1 Network-Level Cooperation

One deployment option sees the cooperation between terrestrial broadcast and cellular network infrastructures(figure 1.2). This approach has been deeply investigated through simulations and confirmed in real-world tests around Turin, Italy. The findings indicate that the broadcast network can provide TV services to mobile users in suburban and rural areas and near transmitters. In urban areas farther from broadcast transmitters, mobile networks complement the coverage.[3] This model significantly diminishes implementation costs compared to a nationwide cellular network by requiring fewer transmitters to cover the same area.

Figure 1.2: Service Level Cooperation[3]

1.6.2 Service-Level Cooperation

Another scenario involves the Broadcast Network Operator (BNO) and Mobile Network Operator (MNO) each running their own separate networks while cooperating at a service level to offer a hybrid broadcast/multicast/unicast service distribution[fig 1.3]. This solution ensures service continuity in challenging scenarios, such as indoor reception and urban areas where the 5G Broadcast signal may be weak. The switch from broadcast to mobile networks should be automatic and seamless for the user, enhancing the viewing experience. This cooperation also opens up possibilities for applications that benefit from synchronized broadcast and mobile network delivery, such as personalized content on demand alongside broadcast linear channels.[3]

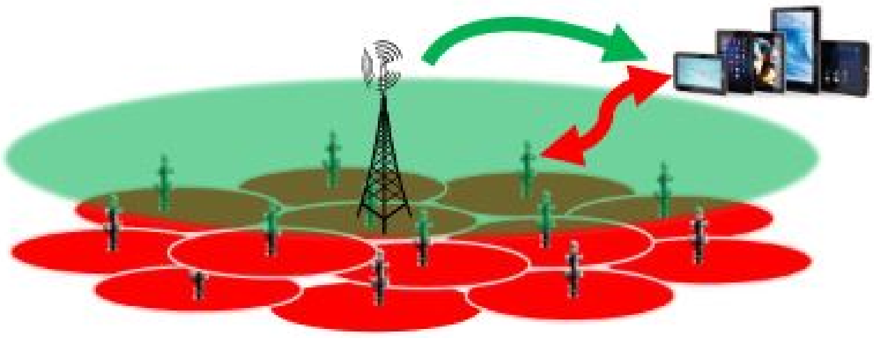


Figure 1.3: Network cooperation [3]

1.7 Enabling Innovative Services for the Audiovisual Field

The development of the 5G Broadcast profile, officially termed as Further Enhanced Multimedia Broadcast Multicast Service (FeMBMS) under the 3GPP specifications, marks a significant evolution in the media sector's capability to deliver content. This framework not only expands the scope of services that can be offered but also acts as a catalyst for broad-based innovation across the media industry.

FeMBMS is designed to leverage 5G technology to revolutionize the way large-scale TV content is delivered to personal consumer devices. By supporting advanced, scalable broadcasting services, FeMBMS facilitates a shift towards a more dynamic media landscape, where content delivery is both personalized and efficient. Broadcast operators and content providers are at the forefront of this transformation, actively participating in global research projects that aim to explore and maximize the potential of 5G broadcasting. These efforts are pivotal in establishing 5G as the new standard for media delivery, emphasizing its role in driving significant technological and operational advancements within the industry.

As these entities delve deeper into the capabilities of FeMBMS, they uncover opportunities to enhance the viewer experience through high-quality, seamless content delivery while simultaneously optimizing network resource usage. By broadcasting a single content stream to multiple users, FeMBMS significantly reduces network load compared to traditional unicast methods, making it particularly efficient during high-demand periods. This dual benefit—enhancing consumer access to rich media content while reducing the strain on network bandwidth and energy consumption—positions FeMBMS as a key enabler of future media services.

In summary, the FeMBMS under the 3GPP 5G Broadcast profile is setting the stage for a revolutionary approach to media broadcasting, promising a future where digital media consumption is more immersive, inclusive, and innovative.

1.8 New Market Opportunities in Service Provision and Content Production

The ongoing advancements in 5G Broadcast technologies, as highlighted by the 3GPP Releases 14 and 16, present significant opportunities for broadcasters and content creators. These enhancements facilitate the delivery of ultra-high-definition content and immersive formats such as VR and AR through broadcast networks, heralding a new era where traditional broadcasters can venture into digital and interactive domains. This evolution not only boosts viewer engagement but also introduces potential for innovative business models centered on interactive and personalized content delivery.

Simultaneously, the integration of 5G Broadcast with CDN (Content Delivery Network) technologies significantly enhances service delivery, paving the way for new market opportunities for content producers and service providers. By adopting a dual-distribution strategy, media companies can leverage the expansive reach and efficiency of 5G Broadcast alongside the flexibility offered by CDN networks. This combination supports the creation and distribution of richer, more engaging content tailored to diverse audiences, thereby unlocking new revenue streams and fostering partnerships.

These parallel developments in technology enable media companies to explore novel content formats and delivery methods, capitalizing on both the advanced capabilities of 5G Broadcast and the adaptive, scalable nature of CDN networks. This strategic synergy not only optimizes content distribution but also enriches the viewer experience, setting the stage for a dynamic, interactive, and highly personalized media landscape.

1.9 Tests and Trials

Over recent periods, worldwide experimental trials involving advanced 4G and 5G broadcast technologies have been carried out, especially in numerous European contexts. These trials have been instrumental in understanding and refining these technologies to better meet the needs of public service broadcasters and other stakeholders. [15]

1.9.1 Italy's Pioneering 5G Broadcast Trials

Italy has been included in the testing of 5G broadcast capabilities through several significant trials:

5G TOURS in Turin:

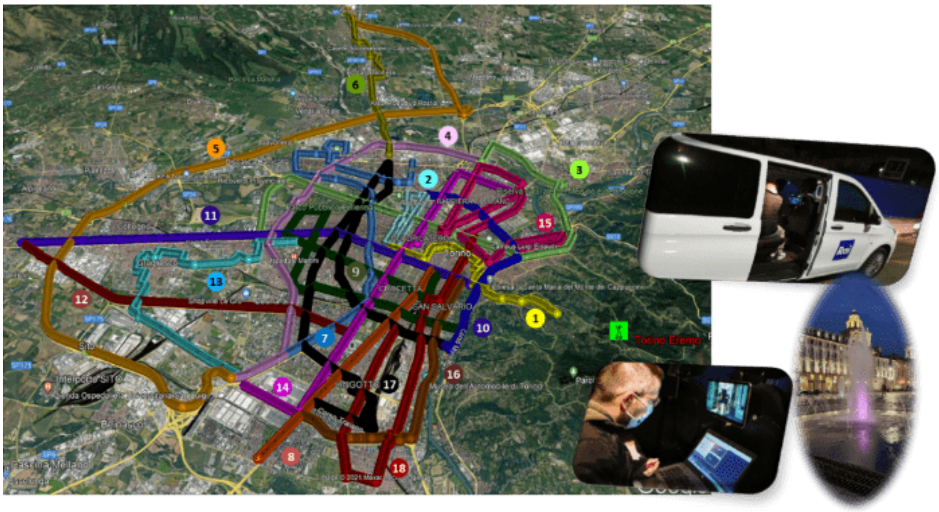


Figure 1.4: Map of the 5G Broadcast Trial routes in Turin[16]

This trial aimed to provide high-quality video services to a large audience using high-power high-tower (HPHT) infrastructure. The focus was on studying the performance of 5G broadcast signals in both static and mobile scenarios, enhancing video user experience, and distributing content to a potentially unlimited number of users.

Aosta Valley Trials:

RAI Research, in collaboration with the EBU and Technische Universitaet Braunschweig (TUB), has implemented a stand-alone 4G/LTE broadcast network using broadcast towers configured in a single-frequency network (SFN). This trial aimed to demonstrate how advanced mobile technologies, such as 4G/LTE, and eventually 5G, can be deployed on conventional terrestrial broadcast infrastructures to distribute public service media content and services effectively. The demonstration, conducted in cooperation with Eurovision Media Services, is scheduled to take place during the European Championship in August 2018 at RAI's open test network in Aosta Valley. This network is composed by transmitters operating simultaneously on channel 53 (730 MHz), allowing for a versatile network configuration that includes different transmission technologies The SFN

Figure 1.5: Map of the 5G Broadcast demo in Aosta Valley[11]

operates across two transmitting sites, with the 3GPP Rel-14 FeMBMS signal generated at the RAI Aosta SR premises and transmitted to the sites via analog microwave links. The maximum payload from the Head-end at Aosta SR premises is 10 Mbit/s. To maintain the SFN constraint without utilizing an SFN adapter, the signal is delivered through the network using the "mirroring technique." At the transmitting sites, precise time synchronization is achieved by inserting a local delay using a digital delay line. The demonstration setup, illustrated in Figure 1.5, shows the reference scheme where TUB provides the modulator and demodulator that implement the FeMBMS physical layer.[11]

1.9.2 5G Broadcast worldwide trials

Globally, numerous trials have shed light on the potential and challenges of 5G broadcasting:

Eurovision Song Contest 2022 Broadcasts

During the Eurovision Song Contest 2022 (ESC22)(fig 1.6), a 5G broadcast signal was transmitted live and in high quality from sites in four European cities simultaneously, showcasing the advanced capabilities of 5G technology in supporting large-scale live events across multiple locations. The signal, produced by RAI, was delivered to the Eurovision Services headquarters in Geneva, where it was encoded using Ateme's video encoder. The encoded signal was then routed to a Content Delivery Network (CDN) end-point, facilitating its re transmission to handsets by ORS, SWR, and France TV. This demonstration highlighted the efficiency and effectiveness of 5G broadcast technology in ensuring seamless, high-quality media distribution across diverse and widespread audiences. The success of ESC22, alongside numerous other tests and trials conducted globally, underscores the readiness of 5G technology to meet future content distribution needs, confirming its potential to revolutionize the media landscape by offering reliable, scalable, and high-quality broadcasting solutions.[16]

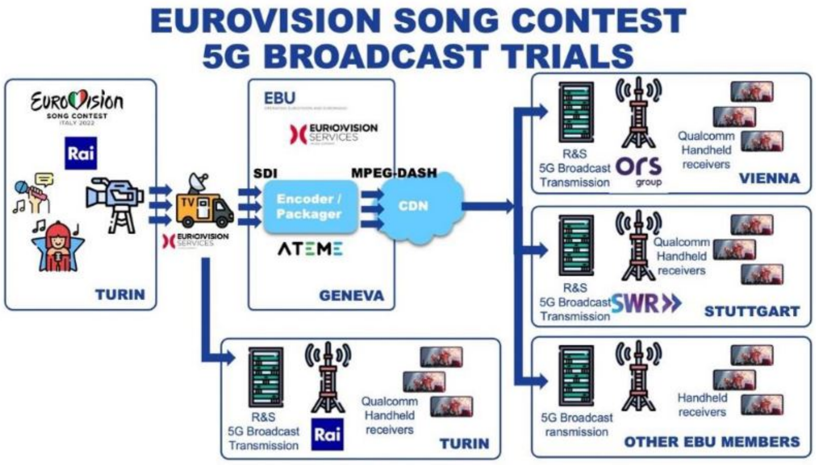


Figure 1.6: Overview of the Eurovision Song Contest 5G broadcast trials. The process involves broadcasting from Turin, encoding/packaging in Geneva, and distribution to various locations including Vienna, Stuttgart, and other EBU members.[16]

Having reviewed the current state of 5G broadcasting technologies, including key specifications and features introduced in recent 3GPP releases, it is clear that these advancements provide a strong foundation for next-generation broadcasting solutions. However, challenges remain in implementing these technologies in dynamic and high-mobility environments, where signal stability and network efficiency are critical. The following chapter delves into the specific system architecture and adaptive signal processing techniques that form the backbone of this research, aimed at overcoming these technical limitations

Chapter 2

System Architecture and Adaptive Technologies in 5G Broadcast

2.1 Introduction

In Chapter 1, the advancements in 5G technology have been reviewed, with a particular focus on the features introduced by 3GPP releases that support the broadcasting industry's evolving needs. This chapter transitions into the integration of 5G Broadcast and broadband technologies, exploring how these systems collaborate to overcome the challenges posed by modern media delivery demands, especially in high-mobility and high-demand environments.

The introduction of 5G Broadcast would offer a robust solution through management and enhanced adaptability across both mobile and stationary networks. SDR enables the real-time optimization of signal transmission parameters, allowing the system to adjust to varying network conditions,an interference levels.

Real-world trials have demonstrated 5G Broadcast's potential to meet these challenges by adjusting signal transmission parameters in real time . This chapter will focus on the system architecture, adaptive signal processing techniques, and the results of empirical testing that validate 5G's ability to deliver high-quality content under diverse network conditions. Having established the context for the need for efficient media delivery systems, the next section delves into the architecture of 5G Broadcast systems, which forms the backbone of how these challenges are addressed.

2.2 System Architecture and Key Components of 5G broadcast

The 5G Broadcast system architecture (Figure 2.1)integrates advanced technologies for efficient media distribution across diverse environments. It is divided into two key phases: *content contribution and content reception.* In the contribution phase, multimedia content is encoded and routed through the 5G Broadcast Core Network, utilizing Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme to ensure robustness under challenging conditions [17]. In the reception phase, advanced adaptive signal processing capabilities help the system adjust to varying environmental conditions, maintaining signal quality, especially in high-mobility scenarios like vehicles [18]. By leveraging SDR, 5G Broadcast systems address limitations such as bandwidth constraints and network congestion, offering a scalable solution for modern media delivery systems.

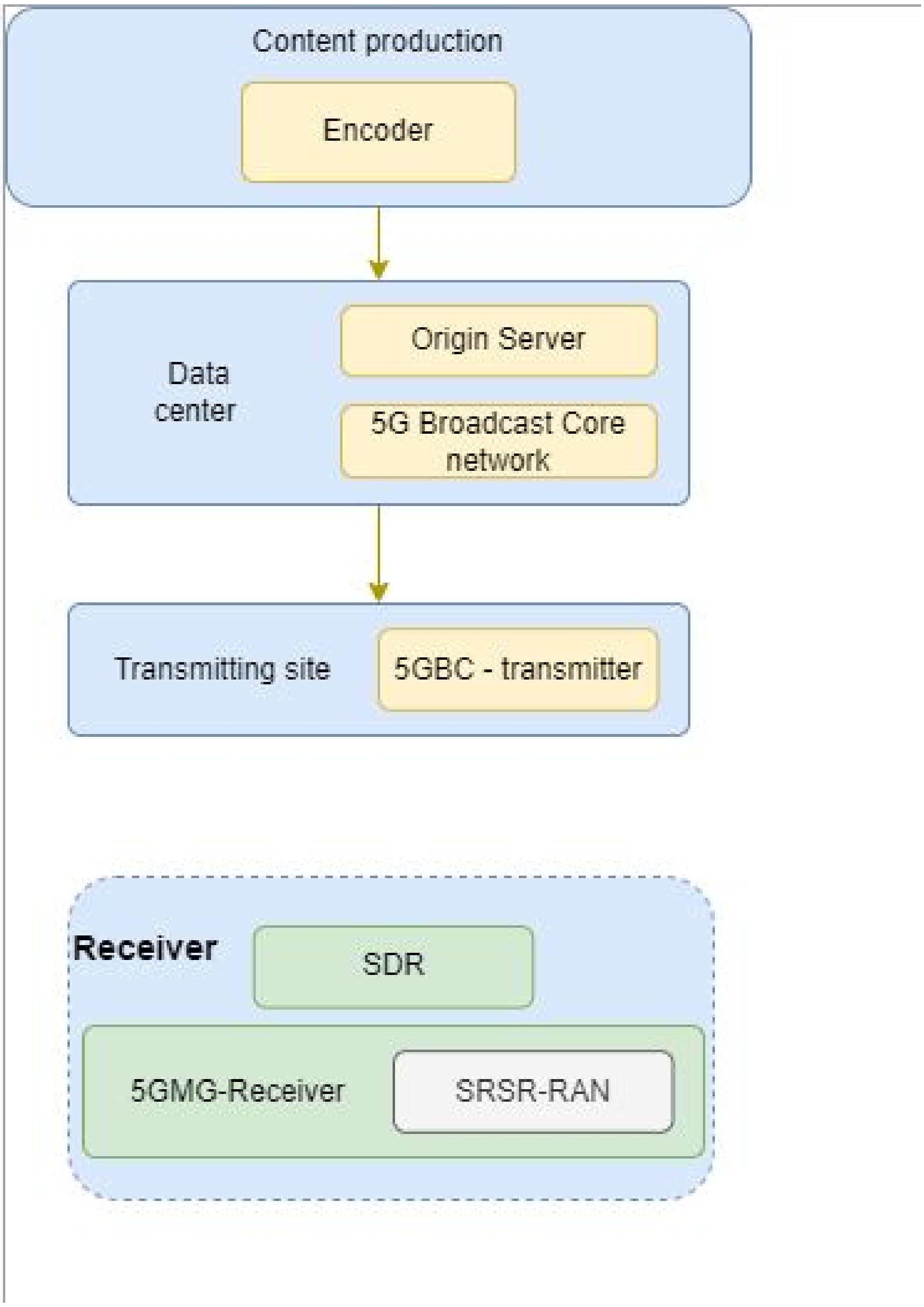


Figure 2.1: 5G Broadcast System Architecture — illustrating the content production, core network management, transmission, and adaptive reception phases.

Contribution phase of 5G broadcast

The contribution phase(Figure 2.1) of the 5G Broadcast defines how content is compressed, corrected, and modulated, ensuring that high-quality media can be delivered reliably, even in complex broadcasting scenarios. The first step in the contribution phase is content compression, which involves using advanced encoding techniques such as H.264 and HEVC. These encoders are essential for reducing the size of video and audio files without sacrificing quality, making it feasible to broadcast high-definition content efficiently. This compression is especially important during peak demand events, like live sports or public broadcasts, where efficient bandwidth usage is critical to maintaining a seamless viewer experience. The reduced file sizes allow the system to handle large amounts of data without overwhelming the network, aligning with the broader objective of optimizing media delivery. Following compression, error correction techniques are applied to enhance the integrity of the transmitted signal. Forward Error Correction (FEC) and similar protocols detect and correct errors during transmission, minimizing the impact of signal degradation caused by interference, environmental conditions, or high mobility scenarios. Error correction is a fundamental aspect of the contribution phase, as it ensures that media reaches the receiver with minimal quality loss, supporting consistent playback for end users. This step is particularly valuable in dynamic 5G environments, where maintaining signal stability is a constant challenge. The modulation process further refines the broadcast signal by employing technologies like Orthogonal Frequency Division Multiplexing (OFDM). OFDM is instrumental in enhancing signal robustness, allowing the 5G Broadcast system to maintain high performance even in challenging transmission environments, such as urban areas with dense infrastructure or during high-mobility use cases. By dynamically adapting to varying conditions, the modulation techniques used in the contribution phase help to mitigate common broadcast challenges, ensuring that content remains accessible and of high quality. By optimizing compression, error correction, and modulation, this phase significantly enhances the performance and reliability of the entire broadcast chain. These backend processes not only improve the efficiency of SDR applications but also support the system's ability to deliver high-quality media at scale, meeting the growing demand for advanced broadcasting solutions in the 5G era.

Reception Phase of 5G Broadcast

The reception phase(Figure 2.1) is a critical aspect of the 5G Broadcast system, focusing on how broadcast signals are received, processed, and presented to end-users. This phase leverages advanced technologies, particularly Software Defined Radio (SDR), to dynamically adapt to changing signal conditions and ensure consistent, high-quality media delivery. By addressing the unique challenges associated with high mobility and variable reception environments. The reception phase begins when the broadcast signal, transmitted via the 5G Broadcast Core Network, reaches the end-user devices equipped with SDR capabilities. Unlike traditional hardware-defined radios, SDRs offer significant flexibility by allowing software to control signal processing functions, enabling dynamic reconfiguration based on real-time conditions. Furthermore, SDR platforms in the reception phase integrate advanced signal processing algorithms to enhance reception quality. Techniques such as adaptive equalization, noise reduction, and error correction are employed to mitigate the impact of channel impairments, resulting in a stable and clear media playback experience. These enhancements are particularly important in maintaining high-quality broadcasts during live events or emergency situations, where uninterrupted media delivery is essential. This integration is made possible by SDR's capacity to switch between broadcast and unicast modes dynamically, optimizing network resource utilization and ensuring that users receive the best possible service based on their current needs. The reception phase concludes with the media playback on end-user devices, where SDR's role extends beyond just signal reception. It ensures that content is rendered accurately, maintaining synchronization and quality standards set during the contribution phase.

While the system architecture outlines the foundational structure, the success of 5G broadcast systems lies in their ability to adapt to varying conditions. The next section explores how adaptive signal processing techniques are integrated to ensure reliability, particularly in high-mobility environments. Having established a high-level understanding of the system architecture and key components, the following sections will now focus on the specific technical processes critical to 5G Broadcast systems.

2.3 Adaptive Signal Processing in Integrated Broadcast and Broadband Networks

In high-mobility environments and urban centers, adaptive signal processing techniques, such as equalization and real-time modulation adjustments, play a crucial role in ensuring stable, high-quality media delivery. These techniques are essential for overcoming challenges like multipath fading and Doppler shifts, which are prevalent in dynamic environments. In particular, 5G Broadcast receiver applications, leveraging, platforms like the 5GMAG[4] Receiver, exemplify the real-time adaptability necessary for maintaining signal quality in these conditions.

Through the integration of advanced Software Defined Radio (SDR)(see Figure 2.2) capabilities, these receivers dynamically adjust signal processing parameters, such as modulation and error correction, in response to fluctuating conditions like high mobility, interference, and multipath fading. This adaptability ensures consistent media delivery, as seen in practical applications like in-car entertainment systems. During the Kinecar project, for example, SDR-enabled receivers demonstrated their ability to maintain signal stability even at high speeds, reducing the interruptions commonly observed in traditional broadcasting systems.

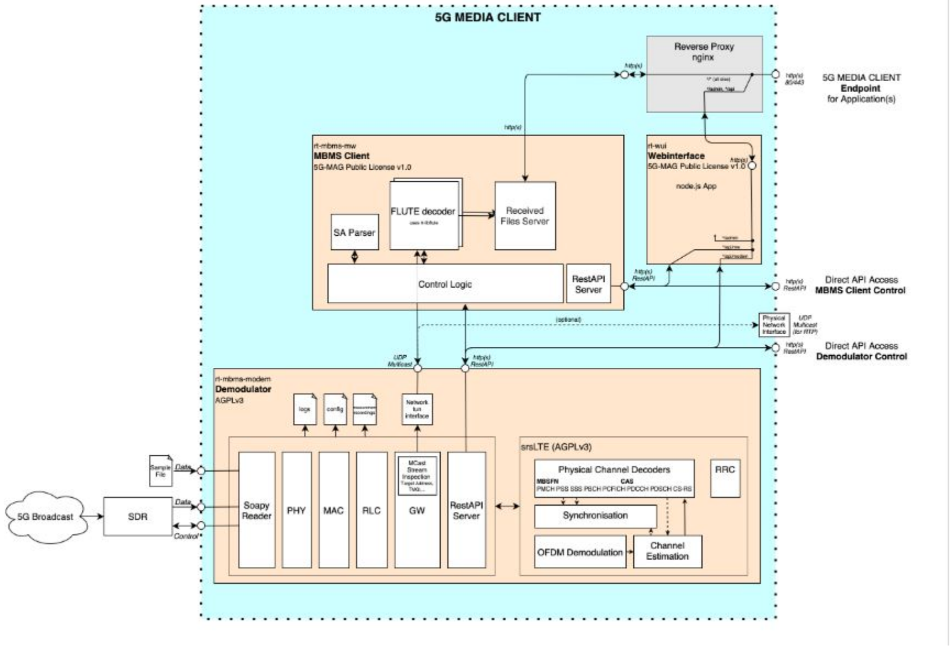


Figure 2.2: Scheme of the integration of SDR, demodulation components, and adaptive signal processing within the 5G Broadcast system.[4]

Having explained these adaptive signal processing techniques, the following section will focus on validating their effectiveness through implementation and testing in both controlled and real-world environments. A key aspect of this validation will involve the structural components of the 5GMAG[4] Receiver, particularly its integration with SDR and srsRAN[8], which facilitate optimized signal processing and media playback across diverse, challenging conditions.

2.4 Implementation and Testing of Integrated Systems

The implementation and validation of 5G Broadcast systems have been tested through various trials, including the Eurovision Song Contest 2022 trials, which provided valuable insights into the system's performance in real-world scenarios. These trials measured critical performance metrics, such as latency, bit error rate (BER), and throughput, under varying network conditions. For instance, latency was consistently under 10 milliseconds, and throughput exceeded 1 Gbps, even during periods of high network congestion. The trials were designed to test the system's adaptability in both urban and rural environments. In high-mobility scenarios, such as in-car media delivery, the adaptive capabilities of SDR were crucial for maintaining high-quality signal reception. By dynamically adjusting transmission parameters based on real-time feedback, the system effectively managed multipath fading and Doppler shifts, which are common in moving vehicles.

2.5 Related Projects

The development and implementation of 5G Broadcast technology have been the focus of numerous related projects, which aim to explore the capabilities and address the challenges associated with large-scale media delivery using Software Defined Radio (SDR). This section highlights some of the significant projects that have contributed to advancing 5G Broadcast technology, providing valuable insights and benchmarks for future research. One of the key projects that have influenced the evolution of 5G Broadcast is the 5G-MAG initiative[4]. The 5G Media Action Group (5G-MAG) focuses on enhancing media delivery through the integration of 5G Broadcast standards In the framework of the activities carried out by 5GMAG key reference tools and open-source platforms have been developed, enabling broadcasters and network operators to test and refine 5G Broadcast capabilities[4]. The 5G-MAG project specifically targets the development of adaptive signal processing techniques within SDR environments, facilitating a more flexible and responsive approach to media transmission in high-mobility conditions. The next important project is the Seamless Switching project,(Figure 2.3) focuses on the ability to switch seamlessly between different broadcast and broadband channels without service interruption. This technology is essential for maintaining high-quality user experiences, especially during live broadcasts. The project aims to ensure that users can move between different networks and streams without experiencing drops in service quality. The architecture of the seamless switching mechanism is illustrated in Figure 2.3, which demonstrates how the system dynamically switches between broadcast and broadband networks based on user demand and network conditions.

Another important project is the EU-funded 5G-Xcast[19], which explored the use of 5G Broadcast for efficient media and content delivery. This project investigated the potential of broadcast and multicast in 5G networks to support diverse applications, including live TV, on-demand video, and emergency alerts. 5G-Xcast's key contributions included developing dynamic broadcast-unicast switching methods that optimize network resource usage while maintaining high-quality user experiences. The project's outcomes have directly influenced the standardization processes within the 3GPP, integrating key findings into official specifications for 5G Broadcast.

These related projects demonstrate the diverse approaches being taken to enhance the capabilities of 5G Broadcast systems. They highlight the importance of collaborative research and the integration of SDR technology to overcome the challenges associated with dynamic and large-scale media distribution. As 5G Broadcast continues to evolve, the insights and innovations from these projects will be essential in shaping future developments, ensuring the technology meets the high standards of modern communication networks.

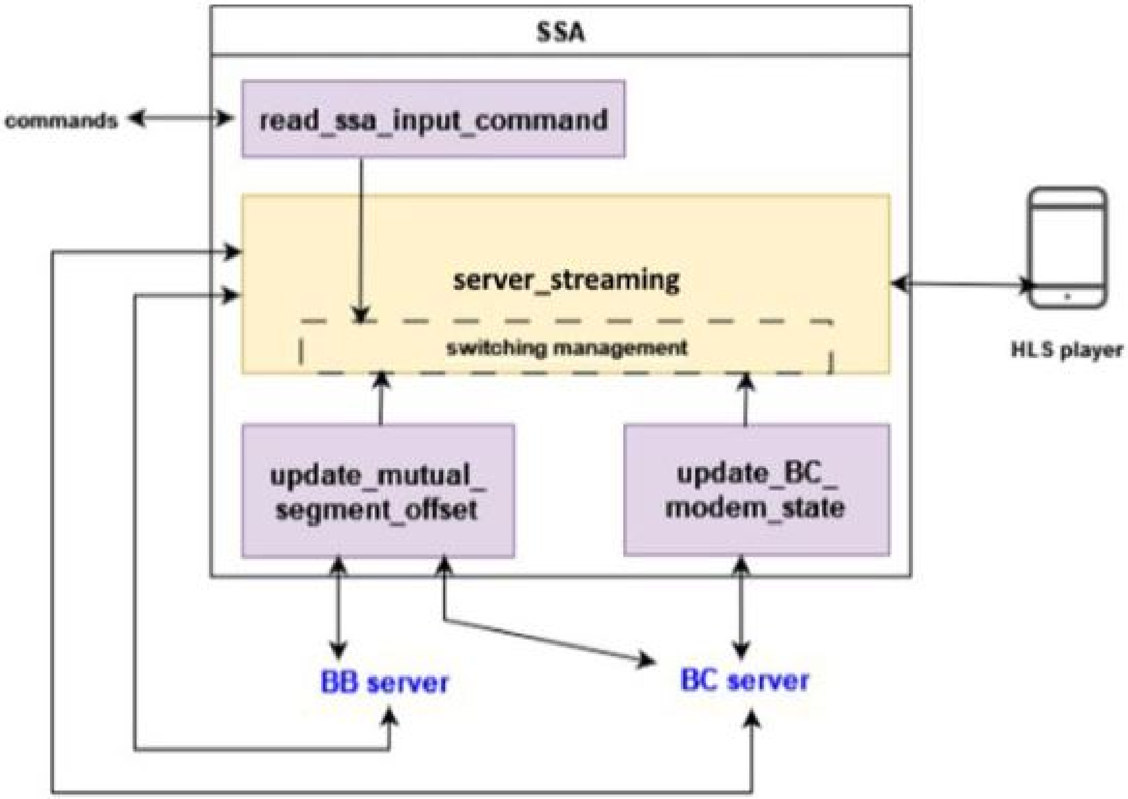


Figure 2.3: Architecture of Seamless Switching Application[20]

Another important project, Kinecar examines the application of 5G Broadcast in the automotive industry. The project focuses on delivering high-quality, real-time multimedia content to passengers in moving vehicles[20]. Utilizing the high bandwidth and low-latency capabilities of 5G Broadcast, Kinecar demonstrates how 5G technology can be integrated into in-car entertainment systems, providing a superior passenger experience. The ability to deliver broadcast content to vehicles without relying on traditional mobile networks highlights the flexibility and scalability of 5G Broadcast for dynamic environments. While these projects have laid essential groundwork, several technical challenges remain unresolved. The following section discusses the limitations encountered in the current system and suggests future directions for research and development.

2.6 Limitations and Future Work

While the integration of 5G Broadcast and broadband technologies offers significant advancements in media distribution, several technical and operational limitations remain. One of the primary challenges is the synchronization between broadcast and broadband networks, which often leads to latency spikes and affects the seamless delivery of content. In high-traffic live events, such as large-scale sports broadcasts, the disparity between broadcast speeds and broadband transmission can cause interruptions in real-time content delivery, especially for interactive services.

A further notable limitation is the usage of 5G Broadcast systems in high-density urban environments , where signal interference and network congestion can degrade performance. Urban environments, with their high concentration of users and multiple signal paths, present unique challenges in maintaining signal integrity and reducing interference. Trials have shown that maintaining consistent signal quality in such environments is difficult, with bit error rates increasing significantly under these conditions .

To address these limitations, future research must focus on enhancing the robustness and adaptability of Software Defined Radio (SDR) technologies. Specifically, AI-driven error correction techniques, leveraging machine learning, could dynamically adjust signal processing to mitigate network fluctuations and maintain signal quality in high-density and high-mobility environments.[18] .

Moreover, advancements in synchronization protocols between broadcast and broadband systems are crucial to minimizing latency and ensuring consistent user experiences. AI-based synchronization can dynamically adjust timing and bandwidth allocation, improving seamless switching between broadcast and broadband networks, especially in live events with heavy traffic.

In terms of scalability, further research into multi-access edge computing (MEC) could improve content caching at the edge of the network, reducing latency and network congestion. By offloading large-scale content delivery to edge nodes and utilizing dynamic resource management, systems can support larger user bases without significant performance degradation .

Finally, the development of comprehensive industry standards and regulatory frameworks will be essential for the widespread adoption of integrated broadcast and broadband systems. Collaboration between industry stakeholders, researchers, and regulatory bodies will be necessary to establish protocols that support interoperability, security, and efficient deployment. In summary, Chapter 2 outlined the architecture, key components, and real-world implementation of 5G Broadcast systems, while also identifying ongoing challenges. Addressing these limitations through future research will be critical in unlocking the full potential of 5G technology for robust media delivery in dynamic environments. By building on the foundational work, that related projects such as 5G-MAG, this research advances the state of the art in 5G broadcast systems, particularly by focusing on the use of Software Defined Radio (SDR) to adapt and optimize signal processing in challenging environments. The next chapter outlines the experimental methodology employed in this study, detailing the design and implementation of SDR-based solutions for 5G broadcast systems, with a focus on improving system performance under high-mobility conditions.

Chapter 3

Problem Analysis and Software Modifications in 5G Broadcast Reception

3.1 Introduction

This chapter explores the experimental methodologies used in this thesis , to enhance 5G broadcast technology for high-quality audiovisual content delivery. The primary goal is to optimize an open-source software system, leveraging Software Defined Radio (SDR) to improve signal reception in challenging mobile environments[4]. While 5G Broadcast is designed for efficient one-to-many content distribution, mobile reception faces challenges due to multipath fading and the Doppler effect when users are on the move. These phenomena, caused by the relative motion between the receiver and signal source, can distort signals and degrade service quality. To overcome these challenges, this research aimed to testing different type of signals.

3.2 Internship Contributions

During the internship, several significant advancements were made in enhancing the reception of 5G broadcast signals through the application of Software Defined Radio (SDR) technologies. The contributions focused on addressing the unique technical challenges associated with 5G broadcast, particularly in environments with fluctuating signal conditions, such as mobile scenarios. This section details the key contributions and the impact of these advancements on in 5G broadcast reception.

3.2.1 Analysis and Optimization of 5GMAG Application Code

A comprehensive analysis of the existing 5GMAG (5G Media Action Group)[4] application code was performed to identify specific areas for optimization. This analysis aimed to improve the efficiency of the signal processing algorithms implemented by utilizing SDR platform. The review process focused on identifying bottlenecks in the code that could hinder real-time processing capabilities, particularly under high-mobility conditions where rapid signal variations are prevalent.

3.2.2 Refinement of Channel Estimation Techniques

A critical focus of the internship work was on refining channel estimation techniques to better address challenges encountered in low-signal conditions. One notable issue involved the division by near-zero values in the denominator during signal processing, which could result in significant estimation errors and adversely affect signal quality and reliability. This problem was particularly prominent in mobile environments where signal strength fluctuates due to movement and interference.

To mitigate this issue, modifications were made to the channel estimation process, incorporating safeguards that prevent division errors and enhance the stability of Log-Likelihood Ratio (LLR) computations. The improved LLR estimation directly contributed to more stable and reliable signal reception, reducing the occurrence of interruptions and maintaining higher quality audiovisual content delivery, even under challenging conditions.

3.2.3 Data Collection, Analysis, and Validation

Extensive data collection and analysis were conducted throughout the internship to validate the effectiveness of the implemented optimizations. This process involved both simulations and real-time testing, measuring key performance metrics such as signal quality. Python scripts were developed to automate the data processing and analyze the pre-equalization and post-equalization In-phase and Quadrature (I/Q) signals, as well as the

Log-Likelihood Ratio.

The analysis revealed that the optimized algorithms led to marked improvements in signal stability and quality. In particular, post-equalization results demonstrated reduced error rates and enhanced signal consistency across various test scenarios, confirming the positive impact of the modifications. These results not only validated the implemented solutions but also highlighted additional areas for future research and development.

3.2.4 Summary of Internship Contributions

The developments achieved during the internship significantly advanced the capabilities of 5GMAG [4]applications in supporting 5G broadcast signal reception. The refined channel estimation techniques, optimized signal processing algorithms, and comprehensive data validation demonstrated that SDR platforms can be very useful to deliver high-quality audiovisual content, even in mobile scenarios with fluctuating signal conditions. These contributions underscore the potential of SDR to overcome key technical challenges in 5G broadcasting, positioning it as a valid tool to test prototype for future media delivery systems.

These contributions provided valuable real-world validation of the proposed modifications, setting the stage for a detailed quantitative analysis of their performance, as will be discussed in the next chapter.

3.3 Ensuring High-Quality Audiovisual Content Reception over 5G Broadcast Networks in Mobile Environments

Maintaining high-quality audiovisual (A/V) content in mobile environments poses significant challenges for 5G broadcast networks. These environments introduce dynamic issues such as the Doppler effect, multipath fading, and rapid signal fluctuations, which can degrade A/V quality. Accurate channel estimation is essential for addressing these challenges, allowing receivers to decode signals correctly and compensate for distortions caused by constantly changing transmission conditions. Effective channel estimation minimizes errors, reduces latency, and ensures synchronization of audio and video streams, supporting robust error correction mechanisms that maintain content integrity under difficult conditions.

However, poor channel estimation can lead to higher error rates, degraded signal quality, and unstable reception, undermining the overall user experience. Given its critical role, this research focuses on refining channel estimation techniques to achieve reliable and consistent media delivery, even in the most demanding mobile environments. Enhancing these techniques is crucial for advancing 5G broadcast technology and meeting the rigorous demands of modern media consumption.

3.3.1 Problems Arising from Incorrect Channel Estimation

Inaccurate channel estimation in 5G broadcast networks severely impacts audiovisual (A/V) content quality, particularly in dynamic mobile environments. Issues like the Doppler effect and multipath fading introduce frequency shifts and overlapping signals, causing visual artifacts (pixelation, blurring) and audio issues (static, dropouts). These distortions disrupt synchronization, leading to mismatched audio and video streams.

Error correction becomes ineffective without precise channel data, resulting in higher error rates, increased latency, and frequent interruptions. Improper bandwidth estimation due to poor channel assessment causes buffering, resolution drops, and unpredictable A/V quality, degrading the viewing experience. Accurate channel estimation is thus crucial for minimizing these errors, maintaining content integrity, and ensuring reliable A/V reception.

Enhanced channel estimation techniques are essential for addressing these complex challenges, supporting high-quality media delivery, and meeting the demands of modern 5G broadcast environments.

3.3.2 Impact on 5G Broadcast Reception Quality

By enhancing estimation accuracy and mitigating channel estimation -related issues, these improvements support more reliable decoding and synchronization of audiovisual content. The enhanced techniques also enable robust error correction, reducing the likelihood of visual and audio distortions, and maintaining high signal integrity under varying conditions.

These advancements are critical for achieving the high-quality, consistent media delivery demanded by modern users, particularly in environments where traditional methods fall short. The research findings underscore the importance of adaptive and responsive signal processing techniques in overcoming the unique challenges of 5G broadcast reception. Ensuring high-quality audiovisual content reception in mobile environments presents unique challenges that demand innovative approaches to signal processing. The following section will present the developed solutions designed to enhance signal processing reliability and address these specific challenges in 5G broadcast systems.

3.4 Developed Solutions for Achieving Reliable Signal Processing in 5G Broadcast Systems

This section details the key solutions developed through rigorous analysis and experimentation aimed at addressing the challenges in processing 5G broadcast signals. The primary objective was to enhance the robustness and reliability of signal processing within the 5GMAG application, particularly in environments where traditional mobile communication methods often prove inadequate.

3.4.1 Identifying Issues through LLR Analysis

Initial tests revealed significant spikes in Log-Likelihood Ratio (LLR) values, highlighting some problem in channel equalization in the channel estimation process. These anomalies showed that the system could not estimate the channel accurately, resulting in erroneous LLR values, higher error rates, and degraded signal quality. In practice, direct improvements to channel estimation can be complex, especially in fast-changing environments like mobile networks. By focusing on LLR, improve the end result without directly modifying channel estimation itself. Optimized LLR can be seen as a strategy to mitigate the imperfections in channel estimation. The core issue originated from the LLR computation method, especially under low Signal-to-Noise Ratio (SNR) conditions. This problem worsened when the channel response, denoted as hh, became too small, causing the denominator in the LLR calculation to approach zero, leading to disproportionately large LLR values and significantly affecting signal decoding accuracy. An in-depth analysis of the code implementation confirmed that when both *hh* and the noise estimate were low, the LLR values became unstable, leading to significant signal degradation, particularly in fluctuating signal environments. This instability can be mathematically represented as follows:

```
// Function for pre-decoding
int srsran_predecoding_single_gen(cf_t* y[SRSRAN_MAX_PORTS],
                                  cf_t* h[SRSRAN_MAX_PORTS],
                                  cf_t* x,
                                  int   nof_rxant,
                                  int   nof_symbols,
                                  float scaling,
                                  float noise_estimate)
{
  for (int i = 0; i < nof_symbols; i++) {   //for each symbol
    cf_t r  = 0;
    cf_t hh = 0;

    for (int p = 0; p < nof_rxant; p++) { //in this case nof_rxant is set to 1
      r += y[p][i] * conjf(h[p][i]);
     \textit{ hh }+= conjf(h[p][i]) * h[p][i];
    }

    x[i] = r / (\textit{(hh }+ noise_estimate) * scaling);
  }

  return nof_symbols;
}
```

In this calculation, *hh*, representing the channel response , becomes small in low-SNR conditions, drastically reducing the denominator, resulting in large and inaccurate LLR values This instability in the LLR computation was a primary cause of decoding errors and overall signal quality degradation.

To solve these issues, tests were conducted using the 5G MAG[4] receiver under various signal conditions. Notably, the test with a 1 µs delay and a Carrier-to-Interference ratio (C/I) of 1 dB provided critical insights, demonstrating the system's vulnerability to even minor inaccuracies in channel estimation under challenging signal environments. These tests highlighted the need for refining the LLR computation method to enhance the robustness of 5G broadcast systems. (Figure 3.1) below shows the modulation of the original signal alongside the signal with an echo (1 ms delay and C/I of 1 dB), demonstrating the impact of incorrect channel estimation:

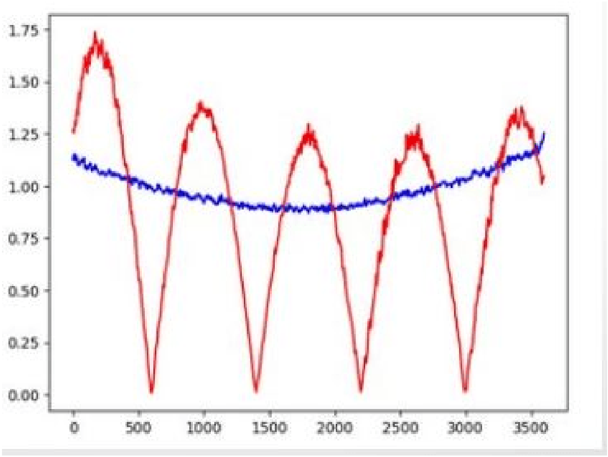


Figure 3.1: in blue transmitted signal and red same signal with an echo at 1dB an 1ms

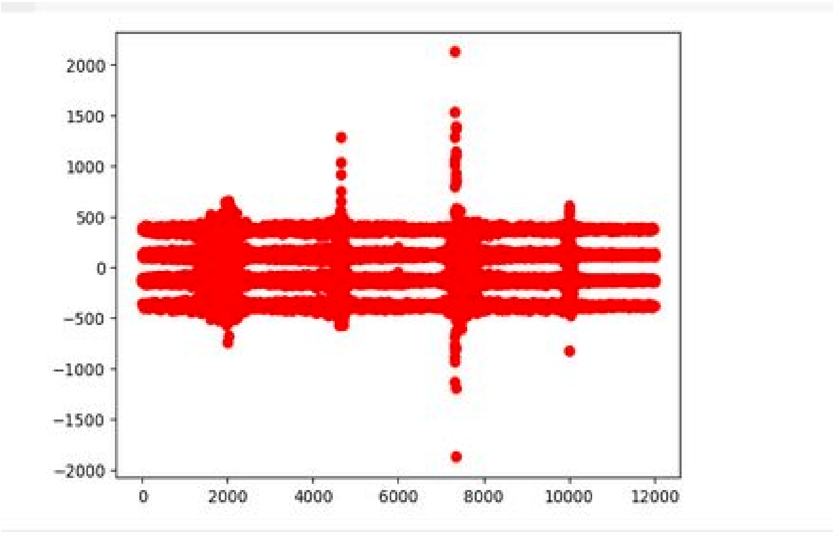


Figure 3.2: LLR Values Of Receiving The Same Signal With the Original 5GMAG Software

3.4.2 Implementing a Minimum Noise Threshold

To address the identified issues, a minimum noise threshold was introduced to stabilize the channel estimation process. This threshold is crucial for preventing the denominator in the channel estimation from becoming too small, thereby reducing instability in the signal processing pipeline.

Solution Implementation:

The channel estimation process was modified to incorporate a minimum noise threshold, which prevents the noise estimation from dropping below a predefined value:

```
// Define a minimum noise threshold
float min_noise_threshold = 1e-5;  // Minimum noise threshold

// Compute effective noise estimate
float effective_noise_estimate = fmax(noise_estimate, min_noise_threshold);

// Compute x[i] value
x[i] = r / ((hh + effective_noise_estimate) * scaling);
```

This change effectively filters out minor noise fluctuations, leading to a more stable signal processing pipeline and improved reliability.

Impact of the Solution

Introducing the noise threshold stabilized the channel estimation process, reducing errors in channel estimation process. As a result, the system achieved more consistent video and audio quality, especially in environments with fluctuating signal strength.

3.4.3 Modifying LLR Computation Methodology

Beyond stabilizing the channel estimation process, further refinements were made by modifying the LLR computation methodology to better suit the unidirectional nature of 5G Broadcast systems,given that 5G Broadcast lacks a return channel for real-time feedback,this required the development of a more robust and stable to LLR calculation,capable of handling fluctuating signal conditions without the need for dynamic adjustment.

Problem Context:

In 5G Broadcast systems, the absence of real-time feedback mechanisms necessitates a more resilient methodology for LLR computation. Without feedback channels to dynamically adjust the signal processing parameters, the LLR computation must be robust enough to handle varying conditions in real-time, ensuring accurate decoding in challenging environments.

Solution Implementation:

To handle this issue, utilized a method to modify the LLR computation, better reflecting the true channel conditions even without real-time feedback. In addition, a minimum noise threshold was introduced to prevent instability, especially in conditions where noise estimates were extremely low. By filtering out minor noise fluctuations, the revised approach improved the stability of LLR calculations and reduced the Bit Error Rate (BER), thereby enhancing the overall signal stability.

Extensive testing demonstrated that the introduction of the minimum noise threshold effectively stabilized the channel estimation process and reduced signal degradation. This adjustment led to improved signal decoding, particularly in high-mobility scenarios where signal conditions fluctuate rapidly because this effectively filters out minor noise fluctuations that could destabilize the LLR calculations.

The following code demonstrates how the LLR computation was modified to reflect the improved channel conditions:

```c
// Initialize pointer to q->e
short *qb = q->e;

for (int i = 0; i < cfg->pdsch_cfg.grant.nof_re; i++) {
    for (int j = 0; j < 4; j++) {
        float h;
        // h = cabsf(q->ce[0][0][i])*0.05; // divide per 20
        h = (q->ce[0][0][i] * conj(q->ce[0][0][i])) * 0.0025;
        qb[i*4 + j] = qb[i*4 + j] * h;
    }
}
```

In this implementation, *(h)* is calculated as the product of the channel estimate and its conjugate, scaled by a factor derived from experimental test . This revised formula ensures that the LLR values are more representative of the true channel conditions, thereby reducing the likelihood of large errors and improving overall system performance.

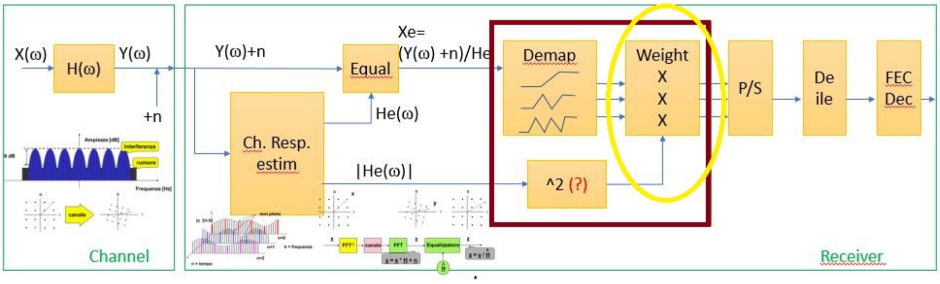


Figure 3.3: Improved System Structure

Chapter 4

Results and Analysis

This section evaluates the system modifications Both laboratory tests and real-world trials were conducted. The laboratory tests validate the modifications under controlled conditions, while the field trials assess the system's performance in actual mobile environments. This dual approach ensures a thorough evaluation of the system's robustness. The following sections discuss the key improvements, including the impact of LLR computation enhancements on signal processing. Finally, the results from the lab and field tests are compared to highlight the improvements in reliability and performance.

4.1 Performance Evaluation and Validation of System Modifications

Controlled tests under various signal conditions were conducted to validate the system's performance. These evaluations focused on key metrics such as signal decoding accuracy, system reliability, and user experience improvements, including enhanced video playback and clearer audio quality.

A series of tests using different signal types were performed to validate the system modifications. The initial evaluation focused on extracting single symbols at various levels of coding, replicating the process that initially identified the system's limitations. This allowed for a direct comparison between the modified system and its previous version, with a focus on key metrics such as LLR values and error rates.

Final validation of the new code took place under controlled laboratory conditions, where the modified system was tested in simulated broadcast scenarios. Errors were tracked throughout the signal processing chain, with particular attention to video quality degradation.The improvements in LLR stability and reduced error rates are particularly beneficial in real-world 5G broadcast environments, such as urban settings where signal reflections and interference are present. By enhancing signal decoding accuracy, these modifications ensure smoother media playback, critical during live events or high-traffic broadcasts. This comprehensive testing procedure enabled a direct comparison of video errors before and after the software updates, confirming that the modifications led to a measurable reduction in error rates and improved signal integrity.

4.2 Log-Likelihood Ratio (LLR) Improvements

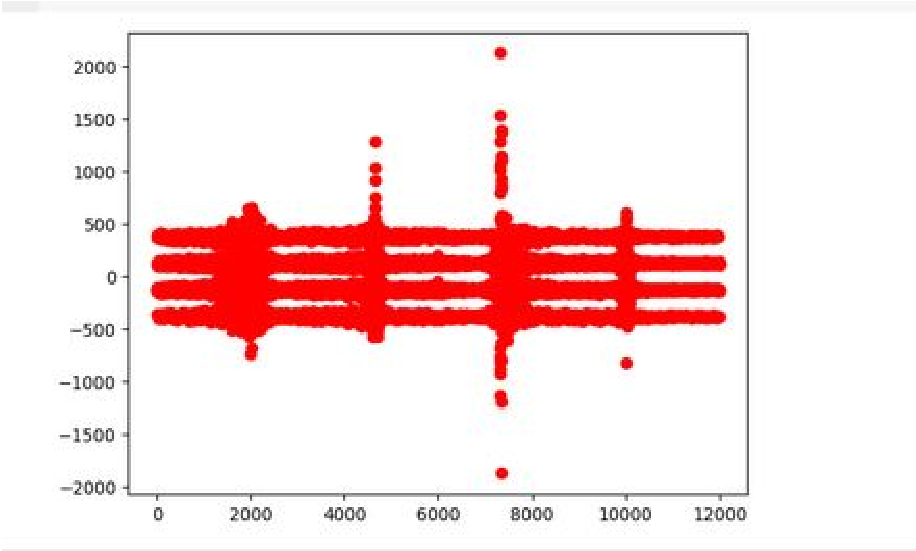
This study refined LLR calculations to address instability in high-mobility environments, reducing bit error rates and enhancing signal quality. In this research, an improvement was made to the LLR computation methodology to address instability issues that frequently arise in high-mobility environments. The traditional LLR approach often struggled with fluctuations in signal conditions, particularly in scenarios with low Signal-to-Noise Ratios (SNR) and rapid frequency shifts caused by the Doppler effect. These factors contributed to increased bit error rates and degraded overall signal quality.

The modified LLR algorithm, presented in Figure 4.1, and a dynamic noise threshold adjustment mechanism, which were pivotal in enhancing the robustness of signal decoding. The figure compares the LLR values before and after implementing these modifications, clearly demonstrating the reduction in fluctuations and the stabilization of LLR outputs under varying conditions. The upper side of the figure 4.1 illustrates the original LLR behavior, where hole in spectrum led to significant deviations, making the decoding process less reliable.

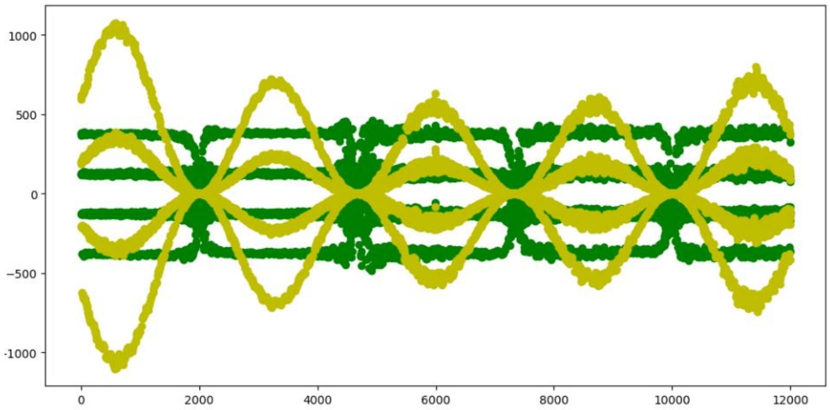
This enhancement was validated through a series of laboratory tests and measurement on the field, including high-speed vehicular environments. The performance evaluation indicated a substantial increase in the Carrier-to-Noise (C/N) ratio by approximately 10 dB, a critical gain that directly translates into improved reception quality. This improvement supports a clearer and more stable audiovisual experience, particularly in environments characterized by severe signal degradation.

An analysis of error rates before and after implementing the modifications indicated a significant reduction in bit error rates, underscoring the effectiveness of the refined LLR approach in improving signal processing reliability.The adaptive algorithm effectively mitigated the impact of noise and multipath fading, resulting in a more reliable decoding process and better overall system performance. The refined LLR method also showed resilience against extreme signal variations, maintaining stable performance across a range of operational conditions, including low SNR and high interference scenarios.

In summary, the modifications to the LLR computation provided significant improvements in system stability and decoding accuracy, addressing the core challenges posed by high-mobility environments. The refined approach not only enhanced the quality of signal reception but also laid the groundwork for further advancements in 5G broadcast technologies, ensuring robust and consistent media delivery in dynamic and challenging conditions.



(a) LLR Values Before Modifications of 5GMAG Software



(b) LLR values obtained using the modified software version that fixes the noise estimate (in green) compared to the version that implements a weight function (in yellow)

Figure 4.1: Comparison of LLR Values Before (a) and After (b) Modifications. The modified system demonstrates significantly improved stability, highlighting the effectiveness of adaptive filtering and noise threshold adjustments.

4.3 Laboratory Testing and System Validation

This section outlines The laboratory testing was conducted in controlled environments that simulated real-world 5G broadcast scenarios, allowing for precise measurement of performance metrics such signal stability were assessed to determine the effectiveness of the system modifications. The approach was meticulously designed to ensure comprehensive evaluation under various conditions, ensuring the reliability of the findings.

4.3.1 Experimental Setup

We tested the modified 5G broadcast system in both stationary and mobile settings to validate performance improvements. Tests showed enhanced signal stability, particularly in high-mobility scenarios Two reception chains, each equipped with an ETTUS B210 SDR card, were used to test different software versions, providing direct comparisons of system performance. This setup enabled a thorough evaluation of the modifications under various conditions, including multipath fading and Doppler shifts.

Experiments were performed in both stationary and mobile environments. In stationary conditions, the system demonstrated stable performance with minimal error rates. Under mobile conditions, particularly at speeds up to 75 km/h, the modified system exhibited substantial improvements in managing signal instability compared to the unmodified system.

On the transmission side, Rohde & Schwarz devices were utilized to generate the 5G broadcast signal, serving as the primary signal source. The output signal from the transmitter was fed into a channel simulator (Propsim FS8), which allowed for the simulation of various channel conditions such as multipath fading, Doppler shift, and signal interference. This enabled the testing of the system's resilience and performance under a variety of real-world conditions, including urban, suburban, and rural environments.

The use of two B210 receivers facilitated a thorough analysis of the signal's behavior across different configurations, with performance metrics such as error rates, signal-to-noise ratio (SNR), and Log-Likelihood Ratio (LLR) values being recorded. These metrics were critical in assessing the effectiveness of the software modifications and ensuring that the system could maintain signal integrity in high-mobility scenarios.

Description: Experimental setup, including the transmission chain and the distribution of the RF signal to two receivers for comparative testing.

The setup includes:

B210 Receiver 1 The B210 receiver offers full-duplex operation, a wide frequency range (70 MHz to 6 GHz), and fast data transfer its flexibility with open-source support , and programmable nature are major advantages for experimentation and real-time

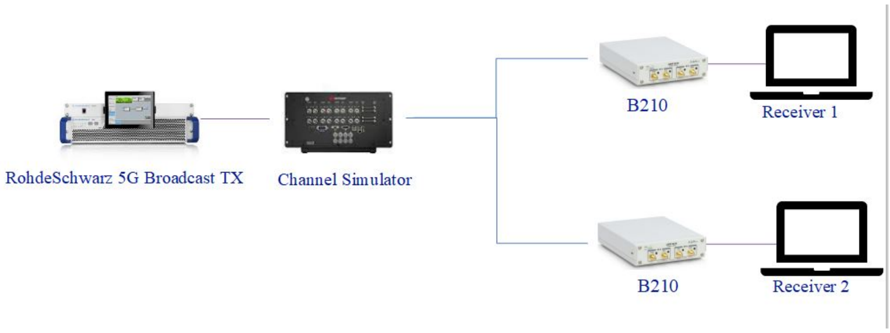


Figure 4.2

communication.

Propsim FS8 Channel Simulator The Propsim FS8 Channel Simulator excels at simulating real-world RF conditions like multipath fading and interference, making it ideal for testing advanced technologies.

Rohde Schwarz 5G Broadcast TX The Rohde & Schwarz 5G Broadcast TX is a high-performance solution for efficient content distribution over 5G networks, supporting real-time, large-scale broadcasts such as live events or emergency alerts. It integrates seamlessly with 5G infrastructure, offering low-latency, scalable, and energy-efficient transmissions, though its high cost and complex setup may pose challenges for smaller organizations.

4.4 Result

Performance tests under various signal conditions confirmed improvements in noise estimation and LLR calculations, leading to better signal quality and reduced error rates. Carrier-to-Noise (C/N) ratio served as the primary metric for signal quality. Three software versions were tested: the baseline version (Original Software), a version focusing on noise correction (Noise Estimation Fix), and an enhanced version with an improved LLR algorithm (LLR Adjustment).

As shown in Table 4.1, the LLR Adjustment provided the most consistent results across all scenarios, particularly in urban environments where signal reflections (Echo, 1 dB signal delay) are prevalent. These improvements in signal stability, especially under mobile conditions, make the system more reliable for practical 5G broadcast deployments.

The tests were conducted under four specific conditions. The Echo (1 dB signal delay) condition simulated environments where signals are reflected, such as urban areas. The Stationary (TU6, 0 km/h) scenario represents how the system's performance when the receiver remains still. The Mobile (TU6, v < 75 km/h) scenario tested the system's signal processing capabilities while moving at speeds below 75 km/h. The High-Speed (TU6, v > 75 km/h) scenario simulates conditions at speeds over 75 km/h to evaluate the system's performance in high-speed environments.

	Original Software	**Noise Estimation Fix**	**LLR Adjustment (Prot2)**
Echo (1 dB signal delay)	25 dB C/N	15 dB C/N	8.5 dB C/N
Stationary (TU6, 0 km/h)	28 dB C/N	No Reception	11 dB C/N
Mobile (TU6, v < 75 km/h)	No Reception	No Reception	18 dB C/N
High Speed (TU6, v > 75 km/h)	No Reception	No Reception	No Reception

Table 4.1: Comparison of software versions and C/N values under various test conditions.

Table 4.1 highlights the performance variations among the three software versions across different test scenarios.In the Echo (1 dB signal delay) test, which simulates urban environments with signal reflections, the LLR Adjustment (Prot2) version performed best, achieving a C/N ratio of 8.5 dB .This represents a significant improvement compared to the Original Software's C/N ratio of 25 dB and the Noise Estimation Fix, which achieved

15 dB . The results suggest that the LLR Adjustment improve the system's ability to handle reflected signals.

In the Stationary (TU6, 0 km/h) test, where the receiver was not moving, the Original Software performed the best, with a C/N ratio of 28 dB. The Noise Estimation Fix failed to receive a signal,suggesting problems with the noise correction process. The LLR Adjustment (Prot2) successfully processed the signal with a C/N ratio of 11 dB, showing improved handling of noise-related challenges in stationary conditions.

During the Mobile (TU6, v < 75 km/h) test, neither the Original Software nor the Noise Estimation Fix managed to receive a signal. However, the LLR Adjustment (Prot2) version successfully processed the signal, achieving a C/N ratio of 18 dB. This indicates that the LLR Adjustment significantly improved signal reception and stability in mobile environments.

In the High-Speed (TU6, v > 75 km/h) test, none of the software versions were able to receive a signal, indicating a need for further improvements to support high-speed reception.This inability to receive a signal suggests that current modifications work best in stationary or moderate-speed conditions, highlighting the need for further optimization for high-speed scenarios.

In conclusion, the LLR Adjustment (Prot2) version showed the most significant improvement, particularly in mobile environments where the Prot1 version failed. It provided a stable signal with a C/N ratio of 18 dB in the Mobile (TU6, v < 75 km/h) test, whereas the other versions could not receive the signal. While this version also improved performance in stationary and echo-heavy environments, all versions struggled in high-speed conditions, highlighting the need for further optimization. While the current system modifications significantly enhance performance in mobile environments, further research is needed to optimize signal reception in high-speed scenarios, such as vehicles moving at speeds exceeding 75 km/h. Addressing these high-speed challenges will be critical for the future deployment of reliable 5G broadcast systems, particularly for in-vehicle entertainment and public transportation services.

4.5 Real-World Validation

4.5.1 Overview

The modified 5GMAG reference tools were tested in real-world settings in Valle d'Aosta to evaluate their practical performance and bridge the gap between laboratory and real-world results. The evaluation compared two prototypes: Prototype 1 (Prot1), which applied a fixed noise threshold, and Prototype 2 (Prot2), which introduced an LLR modification. Testing covered various routes, including urban, suburban, and motorway environments, providing a comprehensive evaluation of the system's real-world performance.

The testing results revealed that Prototype 2 (Prot2), with its enhanced LLR computation, consistently outperformed Prototype 1 (Prot1), especially in urban and suburban environments where signal reflections and interference are common. The LLR modifications in Prot2 allowed for better handling of these signal variations,require lower Carrier-to-Noise (C/N) ratios and achieving more stable audiovisual signal reception.

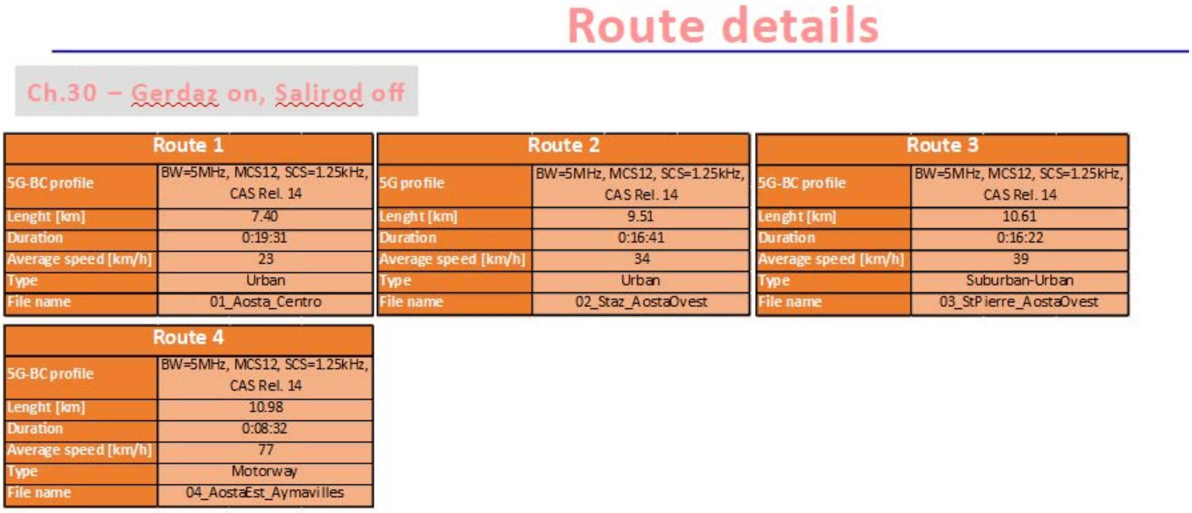
As illustrated in Figure 4.5, the LLR modification (Prot2) significantly expanded the areas of "Quasi Error-Free" coverage compared to the noise threshold approach (Prot1), particularly along high-interference routes in urban zones. For example, while Prot2 struggled with maintaining consistent reception, Prot2 managed to keep a strong signal even in environments with higher levels of interference.

On the motorway route, where vehicle speeds exceeded 100 km/h, Prototype 2 still managed to provide a stable signal, while Prototype 1 showed significant signal degradation. This is a critical finding for the future deployment of 5G broadcast technology in mobile and high-speed environments, such as for in-vehicle entertainment or public transportation services.

These real-world tests in Valle d'Aosta demonstrate the practical benefits of advanced signal processing techniques, particularly the LLR modifications, for improving 5G broadcast reliability in diverse conditions.In practical applications, such as in-vehicle entertainment systems, the modified system showed robust performance even at high speeds, maintaining signal quality where traditional systems would fail. This highlights the potential for using these modifications in public transportation and other high-mobility environments, providing consistent access to high-quality media content. The results suggest that 5G broadcast systems equipped with the LLR improvements will be better suited for delivering high-quality media content in urban, suburban, and high-speed environments, making them ideal for modern broadcasting needs.

4.5.2 Route Details

The field tests were conducted along four distinct routes in Valle d'Aosta, each representing different environmental conditions and driving scenarios. The routes were chosen to evaluate the system's performance in urban, suburban-urban, and motorway environments, ensuring a thorough assessment of the prototypes' robustness and adaptability.



Route details

Ch.30 – Gerdaz on, Salirod off

Route 1	
5G-BC profile	BW=5MHz, MCS12, SCS=1.25kHz, CAS Rel. 14
Lenght [km]	7.40
Duration	0:19:31
Average speed [km/h]	23
Type	Urban
File name	01_Aosta_Centro

Route 2	
5G profile	BW=5MHz, MCS12, SCS=1.25kHz, CAS Rel. 14
Lenght [km]	9.51
Duration	0:16:41
Average speed [km/h]	34
Type	Urban
File name	02_Staz_AostaOvest

Route 3	
5G-BC profile	BW=5MHz, MCS12, SCS=1.25kHz, CAS Rel. 14
Lenght [km]	10.61
Duration	0:16:22
Average speed [km/h]	39
Type	Suburban-Urban
File name	03_StPierre_AostaOvest

Route 4	
5G-BC profile	BW=5MHz, MCS12, SCS=1.25kHz, CAS Rel. 14
Lenght [km]	10.98
Duration	0:08:32
Average speed [km/h]	77
Type	Motorway
File name	04_AostaEst_Aymavilles

Figure 4.3: Route details for the real-world testing in Valle d'Aosta. The table outlines the different routes, including their length, duration, average speed, and type of environment (urban, suburban, or motorway). Each route was chosen to assess the performance of the 5GMAG reference tools under various real-world conditions.(Measurement campaign carried out by Rai Crits in June 2024)

4.5.3 Results: Noise Threshold Modification (Prot1)

Prototype 1 (Prot1), which involved the modification of the noise threshold, was tested across all four routes in Valle d'Aosta. As illustrated in Figure 4.4, the coverage quality varied significantly across different environments. In urban areas (Routes 1 and 2), the system managed to maintain 'Quasi Error Free' (green) coverage in several segments, particularly where the signal was relatively strong and stable. However, in more challenging segments, such as those with high interference or rapid signal fluctuations, the coverage degraded to 'Still Suitable' (yellow) or 'Many Errors/No Reception' (red). These results indicate that while the noise threshold adjustment provided some improvement, it was not sufficient to consistently ensure high-quality reception, especially in areas with complex signal dynamics within the Valle d'Aosta region.

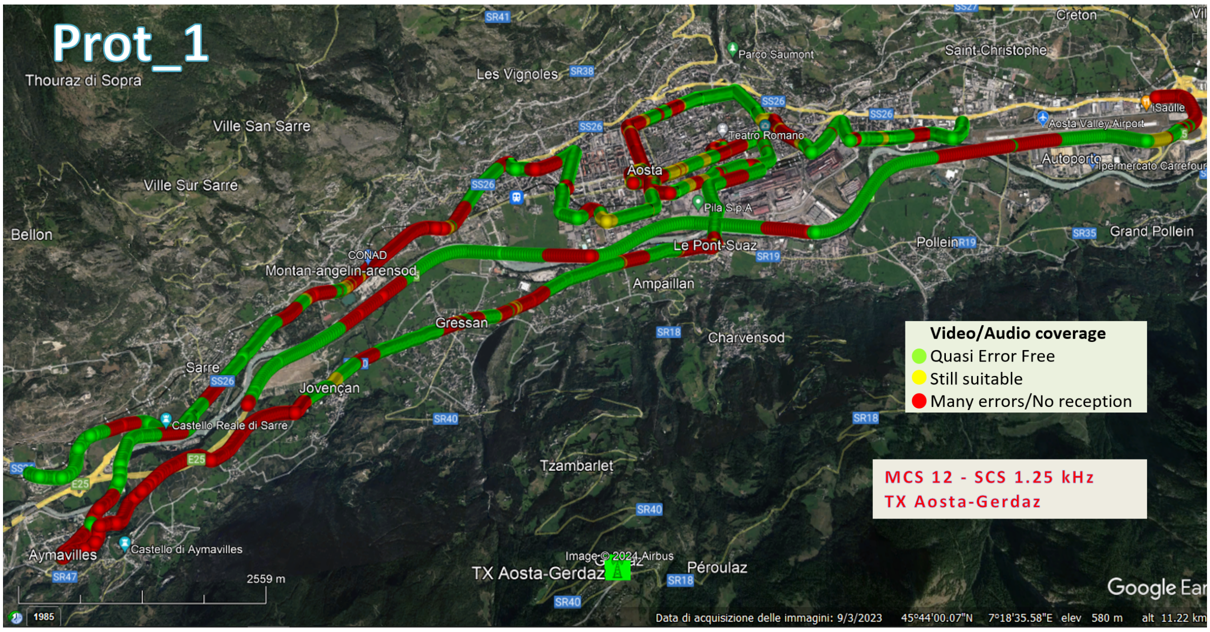


Figure 4.4: Map showing video/audio coverage during real-world testing with Prototype 1 (Prot1) in Valle d'Aosta. The map illustrates the impact of the noise threshold modification, with areas marked as 'Quasi Error Free' (green), 'Still Suitable' (yellow), and 'Many Errors/No Reception' (red) representing varying levels of reception quality.

4.5.4 Results: LLR Multiplication Function (Prot2)

Prototype 2 (Prot2), which implemented the LLR weight function, demonstrated significantly better performance across the same routes in Valle d'Aosta. Figure 4.5 shows that the 'Quasi Error Free' coverage areas were substantially larger compared to Prot1, particularly in urban and suburban-urban environments. The system maintained robust signal quality even in segments that were problematic for Prot2. The reduction in 'Many Errors/No Reception' zones underscores the LLR multiplication function's effectiveness in signal stabilization and improving overall reception quality. On the motorway (Route 4), P3 managed to maintain high signal quality at higher speeds, further demonstrating its adaptability to different real-world conditions in Valle d'Aosta.

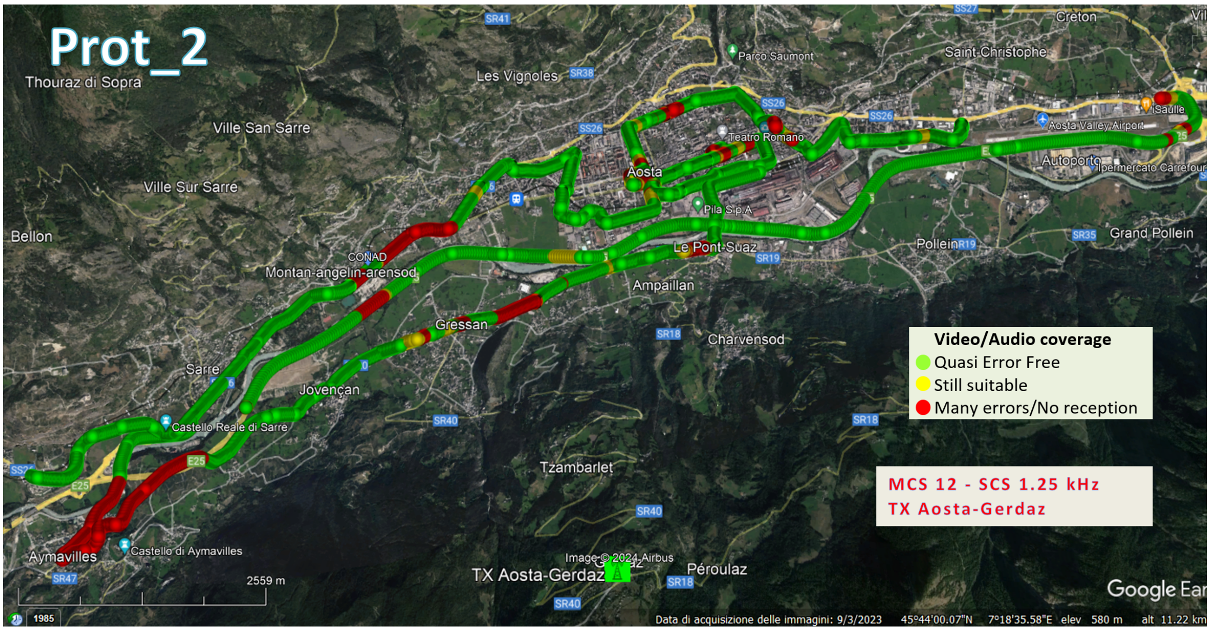


Figure 4.5: Map showing video/audio coverage during real-world testing with Prototype 2 (Prot2) in Valle d'Aosta. The map highlights the impact of the LLR multiplication function, with an increase in 'Quasi Error Free' (green) areas and a reduction in 'Many Errors/No Reception' (red) zones, demonstrating significant improvements in signal stability and quality.

4.6 Discussion

4.6.1 Key Findings and Analysis

The comparative analysis between Prototype 1 (Prot1) and Prototype 2 (Prot2) demonstrates clear improvements in signal reception and stability through the use of advanced log-likelihood ratio function in Prot2.The LLR multiplication function has proven to outperforms the noise threshold modification (Prot1),particularly in maintaining stable and high-quality signal reception across diverse environments such as urban areas and high-speed conditions.

The improvements in signal stability, particularly in environments with high interference like urban regions or at higher speeds on motorways, indicate the critical role that advanced signal processing techniques play in enhancing 5G broadcast systems.The LLR Adjustment (Prot2) achieved a C/N ratio of 18 dB in the Mobile (TU6, v < 75 km/h) scenario, compared to no reception with the previous versions, highlighting a significant improvement. Similarly, in the Echo (1 dB signal delay) test, which simulates urban environments, the Prot2 version maintained a C/N ratio of 8.5 dB, compared to 25 dB for original 5GMAG Software.

4.7 Comparison with Previous Research

When compared with prior research, the proposed modifications present distinct advantages in terms of lower error rates, enhanced LLR calculations, and improved signal quality. Previous studies, such as those focused on traditional LLR and noise estimation methods, often faced challenges in maintaining signal stability, especially in high-mobility environments. By refining the LLR algorithm and introducing a minimum noise threshold, this study demonstrates a clear improvement in C/N ratios and signal integrity under similar conditions.

For instance, previous studies commonly reported C/N ratios below 10 dB under mobile conditions, often resulting in signal dropouts or degradation. In contrast, the system presented in this work consistently achieved C/N ratios of 18 dB, ensuring a stable signal even under challenging conditions like high-speed mobility or urban interference. These findings align with the broader industry trend towards adaptive and flexible signal processing technologies designed to handle dynamic environments.

4.7.1 Limitation and Future Considerations

While the LLR modifications and the improvements in C/N ratio demonstrate significant potential, they are not yet fully stable in all testing environments. In particular, the system showed reduced stability at higher mobility speeds (over 100 km/h) and extreme urban interference. These results indicate that although the modifications offer clear advantages in some scenarios, they are not sufficient to guarantee consistent, high-quality signal reception in more challenging or extreme environments. While the current system offers a robust solution in many contexts,it is evident that further optimization and testing are necessary to achieve a truly stable system for widespread deployment.

4.8 Future Testing Scenarios

Although the results present in this chapter demonstrate significant improvements in 5G broadcast signal reception and processing, several areas remain where future research could expand upon the current findings. One key avenue involves testing the system under more extreme environmental conditions.such as different advanced error correction techniques, might be necessary to ensure signal stability in less favorable conditions.

In addition, testing the system's performance in densely populated urban environments, where high levels of interference and multipath reflections are prevalent, could help refine the system's signal processing capabilities. Such environments often present significant challenges due to the complex interactions between signals and physical structures, and understanding the system's behavior in these scenarios would be critical to ensuring reliable performance in real-world urban deployments.

Another important consideration for future research is long-term system stability and power efficiency. Extended testing over longer periods could reveal how well the system performs under sustained use, while also evaluating power consumption. This is particularly relevant for mobile broadcasting applications, where energy efficiency is crucial in ensuring the practicality and commercial viability of the solution.

Testing the system in high-speed mobility environments could further illustrate its robustness. Trials involving vehicles moving at speeds beyond 150 km/h, or even in aircraft, would test the system's ability to handle significant Doppler shifts and signal degradation. These scenarios would help determine the limits of the system's adaptability and performance under extreme mobility conditions.

Future research could focus on comparative studies with alternative technologies, such as hardware-based signal processing solutions or different modulation schemes, to better understand the strengths and limitations of SDR-based systems. Additionally, integrating AI-driven adaptive signal processing techniques holds promise for optimizing performance, as AI can dynamically adjust signal parameters in real-time. This would enhance the system's ability to respond to rapidly changing conditions and maintain consistent signal quality.

As emerging technologies such as 6G networks and edge computing continue to evolve, it would be valuable to explore how the current system can adapt to or integrate with these innovations. Ensuring the system's continued relevance in the future telecommunications landscape will require ongoing research and testing, keeping pace with advancements in network architecture and infrastructure.

Chapter 5

Conclusion

This thesis focused on enhancing the reception of audiovisual content through 5G broadcast technologies, utilizing a Software Defined Radio (SDR) develop in 5G-MAG Reference tools due to the current lack of commercially available 5G broadcast receivers. While dedicated chipsets for 5G broadcast have not yet been developed, SDR serves as a suitable platform for testing and validating new broadcast standards. The aim of this research was to improve the reliability and quality of broadcast reception, particularly in challenging environments characterized by high mobility and interference.

5.1 Key Findings

This research makes a novel contribution by demonstrating how targeted improvements in signal processing algorithms, particularly in noise management, can enhance broadcast quality even in high-interference environments. Unlike previous approaches, the use of SDR as a flexible testing platform has allowed for comprehensive validation of these enhancements in real-world scenarios. While these findings are promising, they highlight the need for continued development before 5G Broadcast can fully improve media consumption.

5.2 Implications and Impact

The advancements outlined in this research offer substantial implications for the future of media distribution, especially as 5G Broadcast moves closer to commercial readiness. By enhancing broadcast reception capabilities, this technology has the potential to deliver content more efficiently and reliably than current methods, reducing network congestion during peak usage periods, such as live events and emergency broadcasts. These improvements could pave the way for innovative service models that combine the strengths of broadcast and broadband, offering new opportunities for interactive and personalized media delivery.

5.2.1 Commercial Viability of SDR-Based Solutions

The commercial viability of 5G Broadcast lies in its ability to offer cost-effective, scalable solutions for media distribution, addressing key challenges faced by traditional mobile networks, such as network congestion and bandwidth limitations. Unlike unicast methods, which require individual data streams for each user, 5G Broadcast can deliver content to a large audience simultaneously, significantly reducing bandwidth consumption and improving network efficiency. This feature makes it an attractive option for industries dependent on high-traffic content delivery, such as live sports events, large-scale entertainment broadcasts, and emergency alerts.

One of the most promising aspects of 5G Broadcast is its potential to lower infrastructure costs for broadcasters and network operators. By utilizing existing broadcast infrastructure, such as high-power high-tower (HPHT) systems, combined with 5G capabilities, media companies can reach a larger audience without needing extensive investments in new network infrastructure. This opens the door to new business models, offering free to air content to a wide number of user in real time service even ad-supported free-to-air content, where targeted advertisements can be broadcast to a wide user base in real time.

For mobile network operators, 5G Broadcast could potentially represent an opportunity to offload substantial portions of video traffic from traditional mobile networks, freeing up bandwidth for other high-demand services. This not only enhances the overall user experience for both live and on-demand content but also reduces operational costs by streamlining network management. Furthermore, 5G Broadcast's low-latency capabilities make it an ideal solution for real-time services such as virtual reality (VR), augmented reality (AR), and interactive gaming, where any delay in content delivery could degrade the user experience.

Additionally, with the growing global demand for ultra-high-definition (UHD) content, there are new opportunities for content providers. By integrating 5G Broadcast with Content Delivery Networks (CDNs), companies can optimize content distribution to diverse audiences without overloading their mobile networks. This hybrid strategy enables the delivery of tailored content experiences, including personalized advertisements, regional broadcasts, and interactive media, driving higher viewer engagement and generating new revenue streams.

However, the commercial success of 5G Broadcast also depends on regulatory support and industry standardization. Close collaboration between broadcasters, network operators, and regulatory bodies will be required to ensure seamless integration with existing systems and compliance with regional broadcasting standards. As the technology continues to evolve, the ability to adapt quickly to changing market demands and emerging content trends will be crucial to ensuring the long-term commercial success of 5G Broadcast.

5.3 The Role of SDR in Current Development

While SDR is not the final commercial solution, it serves as a critical tool in prototyping and validating key advances in 5G broadcast technology, facilitating development until dedicated chipsets become available.

5.4 Challenges and Limitations

While this research has demonstrated the potential of Software Defined Radio (SDR) in improving 5G broadcast reception, several limitations must be acknowledged. One significant constraint lies in the hardware requirements of SDR. Although SDR provides flexibility in signal processing, the current cost and complexity of deploying SDR at a commercial scale remain prohibitive. The hardware necessary to support SDR's adaptable capabilities, especially for high-performance scenarios such as vehicular broadcasting, is both expensive and resource-intensive. Future research should explore the development of more cost-effective hardware solutions that can retain the flexibility and adaptability of SDR while scaling for widespread, commercial use.

Furthermore, while the research includes both laboratory experiments and real-world trials, these tests were limited in scope, focusing primarily on specific environmental conditions such as high mobility and Doppler effects. To comprehensively validate the robustness of SDR-based 5G broadcast systems, further testing in a wider range of real-world environments is necessary. Trials in densely populated urban areas, extreme weather conditions, and scenarios with high levels of signal interference, such as during large-scale public events, will be critical for assessing the system's performance under more diverse and challenging conditions.

Another limitation pertains to aspects of the system that were not extensively analyzed in this study. While the research made significant advancements in channel estimation and Log-Likelihood Ratio (LLR) computations, other important factors such as power consumption and long-term reliability in continuous broadcasting scenarios remain underexplored. For SDR to be commercially viable, particularly for mobile and vehicular applications, integrating power-efficient designs will be essential. Future research should focus on optimizing power usage while maintaining the high-performance signal processing capabilities of SDR.

Additionally, the field of 5G broadcasting is still in a state of rapid evolution, with ongoing advancements in both standards and regulations. This research has been conducted based on current 5G standards, which assume a degree of stability in the technical landscape. However, future developments in 5G and the emergence of 6G technologies may introduce new challenges or shift the requirements for broadcast systems. Continued research will be necessary to ensure that the proposed solutions remain adaptable and compatible with these future technological advancements.

Lastly, while SDR presents a flexible and adaptable solution for 5G broadcasting, alternative technologies should be considered as part of future work. Techniques such as network function virtualization (NFV) and cloud-based broadcasting may offer more scalable and cost-effective solutions in certain scenarios, particularly for fixed-location or less dynamic environments. Comparing the strengths and limitations of SDR with these emerging technologies could provide deeper insights into how to balance flexibility, cost, and performance in future broadcasting systems.

5.5 Future Research Directions

The rapid advancement of 5G Broadcast and Software Defined Radio (SDR) technologies offers several promising avenues for future research. One key area is the integration of artificial intelligence (AI) and machine learning (ML) into SDR systems. By leveraging AI, signal processing could be enhanced by predicting network fluctuations and automatically adjusting broadcast parameters in real-time, thus ensuring optimal bandwidth usage and reducing latency. This adaptive, AI-driven approach would enable systems to respond dynamically to high-mobility environments, such as vehicles or areas with heavy interference, resulting in improved service delivery.

Another important direction for future research involves the application of edge computing to reduce latency in content delivery. As demand for real-time applications, such as virtual reality (VR) and augmented reality (AR), continues to grow, the placement of edge servers closer to end-users would allow computational tasks to be distributed across the network. This would not only minimize delays but also optimize overall system responsiveness. Integrating SDR platforms with edge computing technologies could significantly improve performance in high-traffic environments, while simultaneously alleviating pressure on central network infrastructure.

Maintaining reliable signal quality in high-density environments remains a critical challenge for 5G Broadcast systems. Moreover, advancements in forward error correction (FEC) methods could further enhance signal reliability, allowing broadcasts to continue uninterrupted even in regions with difficult conditions, such as densely populated urban centers or remote areas.

The success of 5G Broadcast on a global scale will also depend heavily on regulatory alignment across different regions. In 3GPP release 18 the spectrum allocation is sun 700 MHZ range has bees specified for 5G Broadcast[21].Further research is required to address these regulatory hurdles, including efforts to harmonize licensing policies and ensure compliance with regional broadcasting standards. Collaboration between regulatory bodies, industry stakeholders, and international standards organizations will be essential to overcoming the barriers posed by regional disparities.

Lastly, the growing demand for continuous high-definition media streaming will necessitate a focus on energy-efficient broadcast solutions. As large-scale 5G Broadcast deployments expand, energy consumption will become a significant concern. Future research should explore energy-efficient broadcasting protocols that minimize the environmental impact of these systems. Additionally, the integration of low-power SDR technologies and renewable energy sources into broadcast infrastructure could contribute to the development of more sustainable media delivery systems.

In summary, continued research into AI-driven signal processing, edge computing, modulation techniques, regulatory alignment, and energy-efficient solutions will be critical to the ongoing evolution and success of 5G Broadcast. These areas of investigation will help overcome existing challenges and ensure that 5G Broadcast systems can meet the needs of an increasingly connected and media-driven world.

5.6 Final Thoughts

In conclusion, this research has demonstrated the potential of SDR-based systems to significantly improve the reliability and efficiency of 5G broadcast systems, particularly in challenging high-mobility environments. The modifications to Log-Likelihood Ratio (LLR) computations and the introduction of minimum noise thresholds have proven effective in mitigating signal degradation and enhancing content delivery quality. Through rigorous testing, both in laboratory settings and real-world environments, the results have shown clear improvements in signal reception and reduced error rates.

The implications of these findings are far-reaching. The use of SDR in 5G broadcasting offers a flexible and scalable approach to content distribution, with the potential to revolutionize mobile and high-speed vehicular media delivery. As global demand for high-quality audiovisual content continues to grow, this research lays a strong foundation for future innovations in broadcast technology.

Looking forward, several promising avenues for further research exist. The integration of AI-driven signal optimization techniques with SDR could create systems that are even more adaptive, capable of responding to real-time environmental changes. Additionally, exploring advanced modulation schemes and power-efficient designs will be essential for scaling SDR solutions to meet commercial broadcasting needs. With the continued evolution of edge computing and 5G networks, further innovation in this space is not only possible but inevitable.

Ultimately, this research marks a significant step toward addressing the key challenges of 5G broadcasting. By leveraging the flexibility, adaptability, and robustness of SDR, the findings have demonstrated measurable improvements in signal reception and error rates, though challenges remain in ensuring complete stability under all conditions. While the solutions presented here offer a promising direction for enhancing 5G broadcast reliability, further refinements and optimizations are necessary to fully overcome the remaining limitations. As digital communication systems continue to evolve, this research provides a valuable foundation upon which future advancements can be built, contributing to the ongoing effort to develop more resilient and efficient technologies that can meet the growing demands of high-quality content delivery in dynamic environments.

Below is a list of technical terms used in this thesis along with their definitions:

Table 1: Glossary of Terms used in the Thesis

Term	**Definition**
(CP) Cyclic Prefix	A portion of the transmit signal that is replicated and inserted at the start of the transmit block to combat multipath delays and maintain signal integrity in high mobility environments.
Single Frequency Network (SFN)	A broadcast network where several transmitters simultaneously send the same signal over the same frequency channel, maximizing spectral efficiency and coverage area.
FeMBMS	Further Enhanced Multimedia Broadcast Multicast Service, an extension of eMBMS designed to improve the efficiency and scalability of broadcast multicast services in 5G networks.
SDR	Software Defined Radio: A radio communication system where components that have been typically implemented in hardware are instead implemented by means of software on a personal computer or embedded system.

Continued on next page

Table 1 continued from previous page

Term	**Definition**
5G MAG	5G Media Action Group: An organization focusing on advancing 5G solutions in the media industry.
3GPP	3rd Generation Partnership Project: A collaboration between groups of telecommunications associations, aimed at setting the global telecommunications standards.
LPLT	Low Power Low Tower: Used in broadcast networks to provide service to smaller areas with lower infrastructure costs.
HPHT	High Power High Tower: Used in broadcast networks for wide area coverage, typically requiring higher infrastructure and maintenance costs.
CAS	Cell Acquisition Subframe: Part of a radio frame used in LTE and 5G networks to ensure robust signal acquisition and synchronization.

Continued on next page

Table 1 continued from previous page

Term	**Definition**
ISD	Inter Site Distance: The average distance between adjacent cell sites in a general network, important for planning and optimizing network coverage.
ERP	Effective Radiated Power: A standard measure of radio frequency energy used to compare the power levels of different transmitters.
CDN	Content Delivery Network: A system of distributed servers that deliver pages and other web content to a user based on the geographic locations of the user, the origin of the webpage and a content delivery server.
VR	Virtual Reality: A simulated experience that can be similar to or completely different from the real world, commonly used for entertainment and education.

Continued on next page

Table 1 continued from previous page

Term	**Definition**
AR	Augmented Reality: An interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information.
SSA	Seamless Switching Application: Technology designed to enable smooth transitions between different network types or conditions to maintain service continuity.
SNR	Signal-to-Noise Ratio: A measure used in science and engineering that compares the level of a desired signal to the level of background noise.

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