UNIVERSITAT POLITÈCNICA DE VALÈNCIA

_ TELECOM ESCUELA TÉCNICA VLC SUPERIOR DE INGENIERÍA DE TELECOMUNICACIÓN

DESIGN AND PERFORMANCE EVALUATION OF A 5G NEW RADIO BROADCAST MODE FOR SINGLE FREQUENCY NETWORKS

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Abstract

Broadcast technologies are widely extended solutions for point-to-multipoint (PTM) communications as they allow to deliver content to an infinite number of users simultaneously, using a fixed number of resources. Single Frequency Networks (SFN) are one of the most extended broadcast deployments since they offer a more efficient use of the scarce radio spectrum in comparison to multi-frequency conventional deployments. SFNs can be deployed in ATSC 3.0 (Advanced Television Systems Committee – Third Generation) and 4G LTE eMBMS (Fourth Generation Long Term Evolution – evolved Multimedia Broadcast Multicast Services), which are the current state-of-the-art standards for Digital Terrestrial Television (DTT) and cellular broadcasting, respectively. This MSc. Thesis analyses the introduction of broadcast capabilities in 5G New Radio (5G NR), the fifth generation of mobile communications systems recently defined in the 3GPP (3rd Generation Partnership Project) Release 15. To that end, an efficient physical layer design is proposed and its performance is evaluated in SFN scenarios by means of link level simulations. The influence of different physical layer parameters such as transmission modes, cyclic prefix lengths and pilot patterns is also analysed in order to compare 5G NR Broadcast performance with ATSC 3.0 and 4G LTE eMBMS technologies in SFN deployments.

Resumen

Las tecnologías de radiodifusión (broadcast) son soluciones ampliamente extendidas en comunicaciones punto a multipunto (PTM) ya que permiten distribuir contenido a un número infinito de usuarios simultáneamente, usando un número fijo de recursos. Las redes de frecuencia única, en inglés Single Frequency Networks (SFN), son los despliegues broadcast más utilizados ya que hacen un uso muy eficiente del escaso espectro radioeléctrico con respecto a los despliegues multifrecuencia de red convencionales. El estado del arte en cuanto a tecnologías broadcast para Televisión Digital Terrestre (TDT) y para redes celulares es ATSC 3.0 (Advanced Television Systems Committee – Third Generation) y 4G LTE eMBMS (Fourth Generation Long Term Evolution – evolved Multimedia Broadcast Multicast Services), respectivamente. Este TFM analiza la introducción de una componente broadcast en 5G New Radio (5G NR), la quinta generación de sistemas de comunicaciones móviles recientemente definida en la Release 15 del 3GPP (3rd Generation Partnership Project). El TFM propone un diseño eficiente de la capa física (interfaz radio) cuyo rendimiento ha sido evaluado mediante simulaciones de nivel de enlace en escenarios SFN. El TFM analiza la influencia de distintos parámetros de capa física y modos de transmisión, como prefijos cíclicos y patrones de pilotos, con el fin de comparar el rendimiento de 5G NR Broadcast con las tecnologías ATSC 3.0 y 4G LTE eMBMS en despliegues SFN.

Resum

Les tecnologies de radiodifusió (broadcast) són solucions àmpliament esteses en comunicacions punt a multipunt (PTM) ja que permeten distribuir contingut a un nombre infinit d'usuaris simultàniament, utilitzant un nombre fix de recursos. Les xarxes de freqüència única, en anglès Single Frequency Networks (SFN), són els desplegaments broadcast més utilitzats ja que fan un ús molt eficient de l'escàs espectre radioelèctric respecte als desplegaments multi-freqüència de xarxa convencionals. L'estat de l'art en quant a tecnologies broadcast per a Televisió Digital Terrestre (TDT) i per a broadcasting en xarxes cel·lulars són ATSC 3.0 (Advanced Television Systems Committee – Third Generation) i 4G LTE eMBMS (Fourth Generation Long Term Evolution – evolved Multimedia Broadcast Multicast Services), respectivament. Aquest TFM analitza la introducció de competències broadcast en 5G New Radio (5G NR), la quinta generació de sistemes de comunicacions mòbils recentment definida a la Release 15 del 3GPP (3rd Generation Partnership Project). Per a això, un eficient disseny de la capa física és proposat i el seu rendiment és avaluat en escenaris SFN per mitjà de simulacions de nivell d'enllaç. La influència de diversos paràmetres de capa física com a modus de transmissió, prefixos cíclics i patrons de pilots és analitzada a fi de comparar el rendiment de 5G NR Broadcast amb les tecnologies ATSC 3.0 i 4G LTE eMBMS en desplegaments SFN.

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Chapter 1. Introduction

In recent years, point-to-multipoint (PTM) communications have become one of the most required services in fixed and mobile communication systems. The growth of the number of users and the demand on multimedia content, the needs of delivering large amounts of information and the appearance of new trending services such as Vehicular-to-everything (V2X) communications, Internet-of-Things (IoT) or Virtual Reality (VR) have motivated the expansion of PTM communications. Currently, broadcast and multicast technologies are the most popular solutions to enable PTM communications. Broadcast allows to deliver the same information to an infinite number of users while consuming a fixed amount of resources. Multicast reuses this concept to deliver the same content to a finite number of customers. Among all the broadcast and multicast possible deployments, Single Frequency Networks (SFN) are one of the most extended solutions since they make a very efficient use of the scarce radio spectrum by transmitting the same signal from different synchronized sites while using the same frequency.

Due to its scalability and spectrum efficiency, traditional fixed television (TV) and linear content delivery were the first use cases where broadcast technology was adopted. After that, the switch from analogue to Digital Terrestrial Television (DTT) meant the final consolidation of broadcast as a technique to deliver popular content to huge amounts of users. As a consequence, first generation of terrestrial broadcast technologies, e.g. Advanced Television Systems Committee (ATSC), Digital Terrestrial Multimedia Broadcast (DTMB), Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) and Digital Video Broadcasting - Terrestrial (DVB-T), were designed to provide fixed DTT services in different regions worldwide. Later on, multiple enhancements were introduced in first generation standards, motivated by the appearance of several technological advances in the communications scope. Second generation DTT standard, DVB-T2, and the current state-of-the-art terrestrial broadcasting standard, ATSC – Third Generation (ATSC 3.0), introduced an OFDM-based solution where new physical layer mechanisms and new transmission techniques allowed to increase the spectral efficiency and the robustness of the systems, approaching the DTT performance nearer to the Shannon limit.

Multicast and broadcast technologies are also a common solution to deliver popular content in mobile communication systems. The 3rd Generation Partnership Project (3GPP) standardization forum introduced the first solution to deliver multicast and broadcast services in mobile networks, i.e. evolved Multimedia Broadcast Multicast Services (eMBMS), in 3GPP Release 9. eMBMS is based on the 4G Long Term Evolution (LTE) technology and among other features, allows the diffusion of a new multicast/broadcast service over Single Frequency Networks (MBSFN) by defining new physical, transport and logical channels. Until the definition of the current eMBMS solution in Release 14, a large amount of enhancements such as Single-Cell PTM (SC-PTM) or MBMS operation on Demand (MooD) have been introduced following a backwards-compatible philosophy. eMBMS Release 14 is the current state-of-the-art in cellular broadcasting and allows to deliver unicast and broadcast services through different transmission modes such as MBSFN, SC-PTM or MooD for different use cases like V2X or Narrow-band IoT (NB-IoT). One of the main novelties introduced in Release 14 is the definition of an enhanced TV mode, (LTE enTV), which is able to distribute traditional TV services for fixed and mobile receivers over the existing cellular network following the traditional terrestrial broadcast configuration.

The expansion of technology and industry is leading to a new era of innovation and progress that in the communications scope has been translated into the design of a new generation of mobile communication systems. In March 2017, 3GPP started the normative work to develop the fifth generation of mobile communications systems, 5G New Radio, (5G NR). This new technological solution is set to be designed towards the landmark of International Mobile Communications at 2020, (IMT-2020), in order to enable the distribution of different communication services in three different usage scenarios: enhance mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). The latest version of 3GPP Release 15, which was published in June 2018, included the first full standardized solution for 5G NR point-to-point (PTP) communications. In it, all the Radio Access Network (RAN) and the System Architecture (SA) aspects needed to enable 5G communications were defined.

Apart from PTP capabilities, the introduction of PTM communications in the 5G NR solution is also considered as an IMT-2020 requirement. Due to the prioritization of the PTP aspects, PTM capabilities were not included into the work plan of Release 15. As a consequence, the discussion about the design of a 5G NR multicast/broadcast solution was postponed to Release 16. In Release 16 early stages, two different multicast/broadcast proposals were presented, being one related to the design of a LTE-based 5G Terrestrial Broadcast solution and another related to the design of a Multicast/Broadcast Mixed Mode. During the 3GPP meeting RAN plenary #80 hosted in San Diego (June 2018), the LTE-based 5G Terrestrial Broadcast Work Item was approved, and therefore it will be considered in Release 16. On the other hand, Mixed Mode Work Item was noted and probably will be treated in further releases.

LTE-based 5G Terrestrial Broadcast Work Item is focused on the creation of a new 5G NR Terrestrial Broadcast solution to deliver traditional TV services, considering the current LTE enTV design as a basis. The work plan to develop this Work Item is divided in two different phases. First, the Study Item phase will evaluate if LTE enTV solution meets all the 3GPP requirements related to the introduction of multicast and broadcast capabilities in 5G. This set of requirements is specified in 3GPP Technical Report (TR) 38.913. After that, if the analysis shows that the LTE solution does not meet all the requirements, the Work Item phase will design a 5G NR Terrestrial Broadcast solution to deliver traditional TV services over the existing cellular architecture.

1.1 Motivation and Problem Statement

Current DTT state-of-the-art technology, ATSC 3.0, is designed to deliver large amounts of information along vast and dedicated network deployments. ATSC 3.0 bases its performance in fixed reception through high power/high tower (HPHT) installations, where dozens of kW are transmitted to reach distances of dozens of kilometres, covering urban and rural areas with high height antenna installations. In addition, ATSC 3.0 allows to deploy SFNs thanks to its physical layer design, which is based in an OFDM-based solution with different FFT sizes, high modulation orders, different code rates (CR) and guard intervals (GI). Thanks to it, ATSC 3.0 is able to provide larger area coverage than conventional broadcast solutions through a downlink-only configuration. However, ATSC 3.0 is not considered as an efficient PTM solution to deliver broadcast services in cellular environments, where the transmission of short bursts of information and power efficient transmissions are required. In addition, ATSC 3.0 is not a 3GPP backwards-compatible solution [1] [2].

The current cellular broadcast state-of-the-art technology, LTE eMBMS, is designed to enable traditional TV content delivering through mobile networks. LTE eMBMS allows fixed and mobile reception in low power/low tower (LPLT). SFN solutions can be implemented in LTE eMBMS through the use of MBSFN capabilities. Among other features, LTE eMBMS also enables the delivery of TV-like content in HPHT deployments thanks to the use of an optimized LTE enTV physical layer design. Nevertheless, the reuse of a cellular broadcasting solution may introduce some limitations for the introduction of specific terrestrial broadcast capabilities.

According to the 3GPP work plan based on the integration of broadcast capabilities in 5G NR and considering the limitations of the existing broadcast solutions, the need of defining a new 5G NR Terrestrial Broadcast mode is the main motivation of this study. In addition, since SFN deployments are the most efficient solution to deliver broadcast services, the new 5G Terrestrial Broadcast solution is evaluated in SFN environments. The analysis performed in this study is only focused on the physical layer, one of the parts of the system that may introduce more limitations on the introduction of broadcast and SFN capabilities.

1.2 Objectives and Project Scope

The main objective of this MSc. Thesis is to design a terrestrial broadcast solution for the 5G NR technology and evaluate its performance in SFN conditions by means of link-layer simulations. To reach that goal, the current terrestrial broadcast state-of-the-art (ATSC 3.0 and LTE enTV) has been previously analysed and evaluated according to different 3GPP requirements. Based on this procedure, the work carried out in this MSc. Thesis has been structured around different specific objectives:

- **State-of-the-Art Overview**
    - To analyse the physical layer of state-of-the-art PTM technologies: ATSC 3.0 and LTE eMBMS Release 14, and the corresponding SFN operation modes.
    - To analyse the physical layer design of the 5G NR Release 15 technology.
- ***Benchmarking Gap Analysis***
    - To define and classify the different 3GPP requirements showed in TR 38.913 related to the introduction of broadcast capabilities in 5G NR.

   - To identify the methodologies needed to evaluate the 5G broadcast requirements of 3GPP TR 38.913.
   - To analyse and evaluate the state-of-the-art technologies for each 3GPP requirement and to determine if the requirements are met or not.
- ***5G NR Terrestrial Broadcast Extension***
   - To investigate the potential extension of 5G NR PTP to 5G NR Terrestrial Broadcast based on the conclusions obtained from the gap analysis.
   - To propose new physical layer and mechanisms for developing a 5G Terrestrial Broadcast solution.
   - To evaluate the proposed solution according to the 3GPP requirements defined previously.
- ***Link-Level Simulator Development***
   - To develop a link-level simulator able to reproduce the 5G NR Terrestrial Broadcast performance in SFN scenarios.
- ***Performance Evaluation of 5G NR Terrestrial Broadcast in SFN Scenarios***
   - To analyse the impact of different physical layer parameters in SFN scenarios.
   - To define a set of Key Performance Indicators (KPIs) able to describe the performance of the systems in SFN scenarios.
   - To evaluate the performance in SFN scenarios and to compare the obtained results with ATSC 3.0 and LTE enTV.

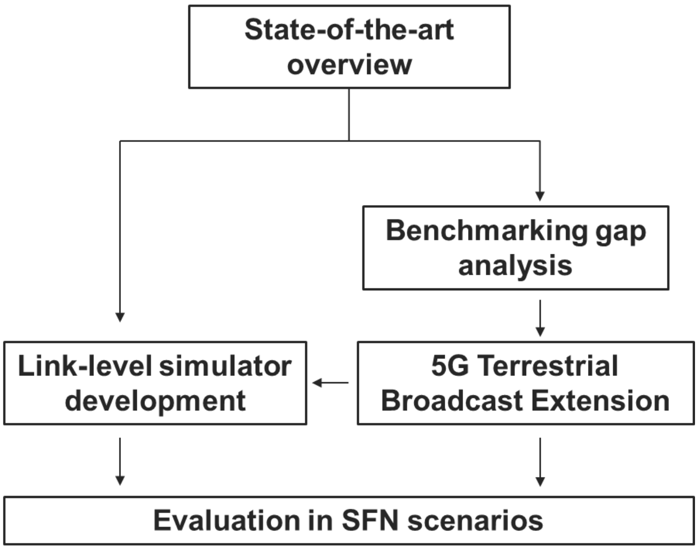

Figure 1. Objectives.

Chapter 2. Methodology

2.1 Study Approach

The current study is focused on the analysis and evaluation of a potential terrestrial broadcast solution for 5G NR according to the 3GPP Requirements specified in [3]. The designed solution has been subsequently evaluated in specific SFN scenarios. Part of the work included in this study has been performed within the 5G-Xcast framework. 5G-Xcast is a 5G-PPP (5G Infrastructure Public Private Partnership) European Project, where the Mobile Communications Group in iTEAM-UPV (Institute of Telecommunications and Multimedia Applications) participates. To carry out this study, different approaches have been performed.

2.1.1 State-of-the-art overview approach

Communication systems are split in different planes depending on the type of information transmitted. In particular, 3GPP and DTT standards are usually composed of the control plane and the user plane. One the one hand, the control plane comprehends all the signalling transmitted between the different elements of the system. On the other hand, the user plane is defined as the set of data transmitted along all the system chain. Even though the analysis of the PTM state-of-the-art carried out in this study has considered both plains, the evaluation and design of the new broadcast solution has been mainly focused on the user plane.

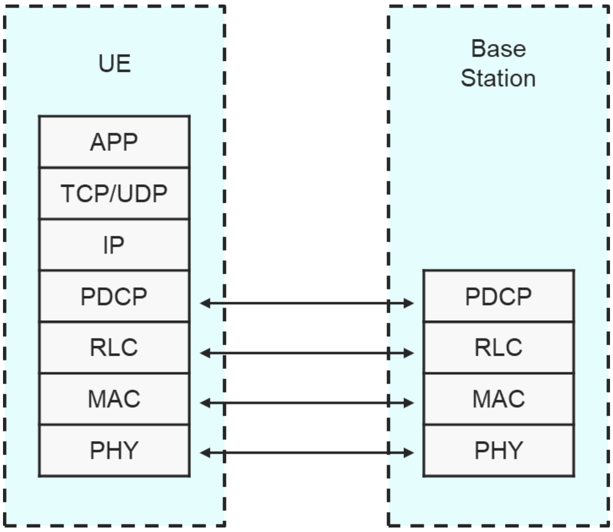

Figure 2. Example of 3GPP Architectural Layers.

Regarding the different architectural layers, the current study has followed the OSI (Open System Interconnection) model – See Figure 2 [4]. In particular, the work performed in this study has been focused on the physical layer, not considering other aspects related to upper layers. Within the physical layer, the analysis has considered the presence of two different elements used to convey the information: physical channels and physical signals. Channels are as flows of information transmitted between different protocol layers. In particular, physical channels segregate and transport the different types of data between the MAC (Media Access Control) layer and the physical layer. On the other hand, physical signals only convey information related to the physical layer and do not exchange information with other layers.

2.1.2 Benchmarking gap analysis approach

To evaluate if the PTM state-of-the-art solutions meet the 3GPP requirements for broadcast transmissions in 5G NR, two different methodologies based on the IMT-2020 benchmarking procedure have been defined [5]:

- **Inspection:** Method applied to those requirements that can be evaluated by looking into the technical specification of the system.
- **Analysis:** Method applied to those requirements that need to be evaluated through mathematical calculations. These calculations may need to use technical information.

In addition, 3GPP requirements have been classified depending on the level of influence in the design of a new 5G NR Terrestrial Broadcast solution. For the classification, two different categories have been defined:

- **Relevant requirements:** Those that are aligned with the design of the terrestrial broadcast solution. These requirements are only related to physical layer aspects.
- **Non relevant requirements:** Those that are not aligned with the design of the terrestrial broadcast solution or not related to physical layer aspects.

2.1.3 SFN evaluation approach

After performing the gap analysis and designing the 5G Terrestrial Broadcast solution, a performance evaluation of this technology has been carried out in different SFN scenarios by defining different KPIs. The definition of these KPIs has also been based on the list of KPIs considered for the IMT-2020 evaluation process [5]. To evaluate the set of KPIs, the methodologies defined for the benchmarking gap analysis have been reused. In addition, a new methodology related to the use of link-level simulations has been also defined:

- **Link-level simulations:** Method applied to calculate the Quality of Service (QoS) of the system by means of a physical layer simulation platform developed in MATLAB language. The simulation platform evaluates the performance of the system through a downlink data connection between the base station and the user equipment. For this study, three different simulation platforms have been used, one for each evaluated technology (ATSC 3.0, LTE eMBMS and 5G NR Terrestrial Broadcast). The ATSC 3.0 and LTE eMBMS platforms have been provided as input for this study by MCG iTEAM-UPV. The 5G NR Terrestrial Broadcast has been developed by the author of this master thesis in collaboration with Samsung Electronics R&D Institute UK (SRUK) as part of the work performed within the 5G-Xcast project.

  The three simulation platforms have been designed following the traditional transmission chain, composed of transmitter, channel and receiver. Parameters setup and error measurement blocks have also been added at the beginning and at the end of the chain to fix the configuration of the transmitted signals and to evaluate the performance of the system. Simulation platform structure is shown in Figure 3 and it is described as follows:

Figure 3. Transmission chain.

- **Parameters setup:** First block of the chain used to specify the parameter configuration of the simulation. All the simulations are carried out by selecting the carrier to noise ratio (CNR) range where the QoS is evaluated. In this master thesis, the QoS has been measured through the block error rate (BLER) parameter. Other specific parameters like Bit-Interleaved Coded Modulation (BICM), framing configuration and additional factors such as the number of antennas for transmission and reception, the channel model considered for the simulation and different methods to estimate the channel can also be configured.

- **Transmitter:** Block used to perform the data transmission. Firstly, an initial number of random bits is created according to the parameters setup configuration. Then, bits are coded and modulated at the BICM chain. After that, complex symbols are mapped and allocated in different time and frequency positions in order to create the final OFDM (Orthogonal Frequency-Division Multiplexing) signal, which is transmitted through the transmitter antenna ports.

- **Channel:** After the transmitter, the OFDM signal is delivered through the free space. In this study, only a channel model emulating SFN scenarios has been considered. More details about the SFN channel model are given in Chapter 6.

- **Receiver:** Block used to receive and detect the transmitted signal. Traditionally, the inverse transmitter process is performed at the receiver. As a consequence, the OFDM signal is disassembled and split in different complex symbols. Then the channel response is estimated and the complex symbols are equalized and de-mapped. At the de-mapper complex symbols are turned into LLRs (Log Likelihood Ratio), a soft information unit related to the log likelihood of the bits to be 0s or 1s. Finally, the soft information is de-interleaved and decoded in order to determine the value of the received bits.

- **Error Measurement:** Final block used to evaluate the performance of the system comparing the bits decoded at the receiver with the transmitted bits. Here, BLER values are calculated for each CNR value. When the BLER reaches the desired value, the simulation stops.

  The transmission and reception chain is not exactly the same for each of the technologies considered in this study. As a consequence, further details related to the transmitter block of each technology are provided in Annex A.

2.2 Project Outline

This subsection describes the structure of the present master thesis, which has been divided in seven chapters and two annexes.

Chapter 1 introduces and motivates the realization of this master thesis. To that end, the use of broadcast technology in cellular networks has been analysed and discussed to motivate the introduction of PTM capabilities in the new 5G NR solution. Based on this topic, the objectives of the thesis have been enumerated and described.

Chapter 2 describes the methodology used to carry out the present study. First, a study approach together with the project outline have been detailed, describing the elaboration process, the structure and the content of each section in the thesis. After that, all the work collected in this study has been divided and distributed in different tasks. The task distribution has been arranged following a chronological planning, which has been structured monthly.

Chapter 3 investigates the principles of the SFN operation in the current PTM state-of-the-art technologies. First, the operation of SFN transmissions has been described and analysed from a technical point of view. After that, the existing broadcast solutions able to perform SFN transmissions have been analysed. The analysis has been focused on the physical layer mechanisms used to deliver broadcast services in terrestrial networks.

Chapter 4 analyses the 3GPP requirements related to the integration of broadcast capabilities into the 5G NR technology. The list of requirements has been classified and selected according to the scope of this study. After that, the fulfilment of the selected requirements has been evaluated through different methodologies for the current terrestrial broadcast states-of-the-art for DTT and cellular environments, i.e. ATSC 3.0 and LTE enTV. The process carried out in this section has been envisaged as gap analysis.

Chapter 5 describes the existing 5G NR solution and analyses the introduction of PTM capabilities in it with the aim of designing a potential 5G Terrestrial Broadcast mode. First, 5G NR physical layer design has been analysed by describing the frame structure and also the physical channel allocation. After that, according to the conclusions drawn in Chapter 4, a new physical layer design is proposed to fulfil the 3GPP requirements and also to enable SFN transmissions. Finally, the fulfilment of the 3GPP requirements by the new solution is again evaluated in this section.

Chapter 6 evaluates the performance of the proposed 5G Terrestrial Broadcast solution in SFN scenarios. To that end, the influence of different parameters related to the operation in SFN environments has been analysed. After that, the performance of the 5G Terrestrial Broadcast solution has been evaluated through the definition of different KPIs. The evaluation of the different KPIs has been carried out through different methodologies, including link-level simulations. The obtained results have been compared with the ATSC 3.0 and LTE eMBMS performance. Finally, some conclusions about this section have been drawn.

Chapter 7 summarizes the main contributions of this master thesis and also proposes a future working plan to integrate the proposed 5G Terrestrial Broadcast solution in the existing cellular network.

Annex A gives a detailed description of the specific transmitter blocks considered for ATSC 3.0, LTE eMBMS and 5G NR link level simulators.

Annex B provides some of the BICM spectral efficiency results obtained by means of link-level simulations for ATSC 3.0, LTE eMBMS and 5G NR.

2.3 Task distribution and temporal planning

The work carried out in this project has been structured in four different tasks, which have been completed during the last year.

Task 1: Research

This first task has been developed in two different phases along the project elaboration. First phase was focused on the investigation of the SFN operation modes and the current DTT and cellular broadcasting states-of-the-art: ATSC 3.0 and LTE eMBMS Rel.14. The investigation process was based on a deep search of information about the physical layer mechanisms used in both solutions to enable SFN transmissions. The first part of this task started in September 2017 and was completed by the end of November 2017.

The second part of the task was focused on the investigation of the new PTP state-of-the-art 5G NR. A similar process based on the analysis of the physical layer design together with the physical layer mechanisms used to deliver unicast services was carried out. This second part started in December 2017 and finished by the end of March 2018.

Task 2: Link-level simulator development

This second task was kicked off at the beginning of December. The investigation over the 5G NR physical layer mechanisms was used to design and develop a 5G NR link-level simulator. The simulator development was carried out in a joint project with Samsung under the 5G-Xcast project. The task was finished by the beginning of June 2018.

Task 3: Air interface design and evaluation

The third task of the project has been focused on the design of the 5G Terrestrial Broadcast air interface solution together with the gap analysis evaluation of LTE eMBMS and ATSC 3.0. This task was built over Task 1 and therefore was started after it, by the beginning of April. The proposal and design of different mechanisms to meet all the 3GPP requirements took over three months.

Task 4: Master thesis composition

The composition of this document has been completed in three different phases, which are directly related to the finalization of the three different tasks. First phase started after the finalization of Task 1 and lasted for two months, since the beginning of February until the end of March. In this first phase, Chapter 3 and part of Chapter 4 were composed. After that, second phase was focused on the composition of Chapter 4, 5 and 6 and was performed from the beginning of April 2018 up to the end of July. Third phase was dedicated to the composition of Chapter 1, 2 and 7 and was carried out during the month of August.

Task	**Q1 (2017)**				**Q2 (2018)**				**Q3 (2018)**			
	Sept	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
1	X	X	X	X	X	X	X					
2					X	X	X	X	X	X		
3								X	X	X		
4						X	X	X	X	X	X	X

Table 1. Task distribution

Chapter 3. State-of-the-art of SFN Operation in Point-to-Multipoint Systems

This section describes the PTM state-of-the-art technologies used to deliver broadcast services by means of SFN operation in terrestrial networks. The analysis is mainly focused on the physical layer.

3.1 SFN Operation

Single Frequency Networks are widely extended deployments used to deliver multimedia content across large areas. SFN principle is based on transmitting the same signal from multiple transmitters at the same frequency in a time and frequency synchronized way. SFN can be deployed in OFDM-based solutions where the use of the Cyclic Prefix (CP) allows the correct demodulation of the signal. At the receiver, the detected signal may present intersymbol interference (ISI) due to the set of artificial echoes coming from multiple transmitters. Depending on the delay of these echoes, the final contribution may result an interfering contribution or a non-destructive contribution that provides certain gain regarding conventional deployments. The time interval where the echoes are considered as useful contributions is defined by the insertion of the GI or CP.

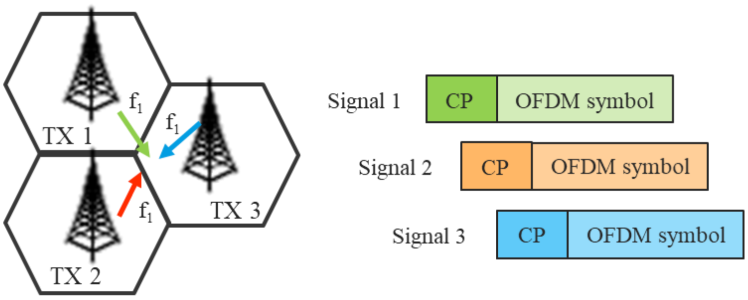

Figure 4. SFN scenario.

The CP insertion covers the maximum echo delay in the network and enables the non-destructive contribution of signals. The CP duration is usually set up to cover the maximum inter-site distance (ISD) between transmitters in the SFN. However, CP introduces some capacity overheads at the expense of preventing inter-symbol interference. The longer the CP, the larger overheads are introduced. Based on this transmission technique, SFNs provide better coverage, less interference, less power consumption and higher reliability than conventional deployments. In addition, the use of a single frequency means a more efficient use of the frequency spectrum, being more frequencies available for other transmissions. SFN deployments are used in DTT and cellular broadcast systems. ATSC 3.0, which is the current DTT state-of-the-art, and LTE eMBMS Release 14, are some of the current OFDM-based technologies to include SFN operation modes.

3.2 ATSC 3.0

ATSC 3.0 is the current DTT state-of-the-art since it offers an efficient and robust solution that overcomes the rest of existing terrestrial broadcast technologies. Based on a complete design that comprises transport protocols, application layer and physical layer, ATSC 3.0 is able to deliver high quality content, e.g. ultra-high definition (UHD), in fixed, vehicular or portable conditions. As main novelty, ATSC 3.0 presents an unprecedented physical layer design based on an OFDM solution that includes efficient codification, multiplexing and transmission techniques such as Low Density Parity Codes (LDPC), Layer Division Multiplexing (LDM) or Multiple-Input Multiple-Output (MIMO) antenna schemes. In addition, the cyclic prefix granularity provided at the physical layer allows ATSC 3.0 to deliver broadcast content through a SFN operation mode. All these features allow to provide ultra-reliable transmissions thanks to a wide range of operative modes. In the following subsections an air interface overview is provided, describing the ATSC 3.0 frame structure and the different parameter configurations [6].

3.2.1 ATSC 3.0 Frame Structure

ATSC 3.0 transmits signalling and data information in ATSC 3.0 frames with a duration between 50ms and 5s. Each frame is composed of different subframes, where each subframe is made up of several OFDM symbols in the time domain and a large number of subcarriers in the frequency domain. Each OFDM symbol contains a total number of subcarriers that is defined by the FFT size and the available system bandwidth. ATSC 3.0 allows three different bandwidths values: 6 MHz, 7 MHz and 8 MHz, being 6 MHz the most common value for a RF carrier in data transmissions. Channel bonding can also be applied to up to two different RF carriers. Regarding FFT sizes, the total number of carriers can be specified by three possible values: 8k, 16k or 32k. Only a part of the total number of carriers is considered as active carriers. The number of active carriers (NoC) is variable and depends on the FFT size and the reduction coefficient. The rest are null carriers and are used as padding when the FFT is applied. The distribution of the different types of subcarriers is shown on Figure 5.

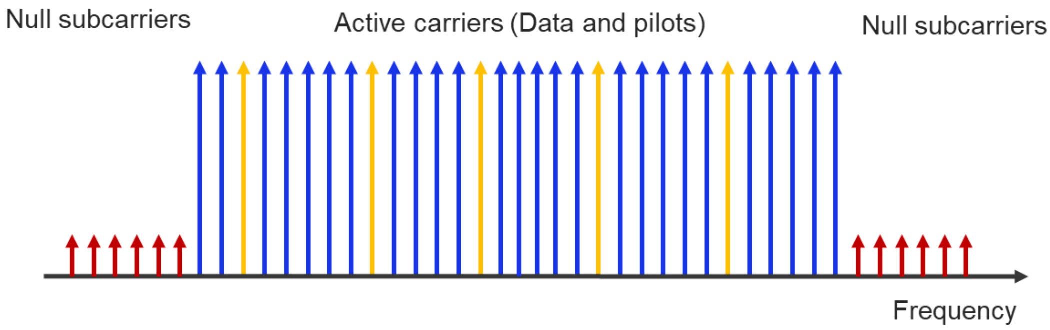

Figure 5. Example of carrier distribution in a OFDM symbol.

The number of OFDM symbols is also variable and depends on the number of active carriers assigned to a OFDM symbol and on the total number of carriers to be transmitted at the subframe. Each OFDM symbol has a GI inserted. GI is an extension of the useful time-domain OFDM symbol, where a fraction of the last part of the OFDM symbol is attached at the beginning. This extension is done in order to prevent ISI due to multipath in fixed and mobile scenarios, e.g. SFN. ATSC 3.0 offers twelve different values of GIs that can be selected depending on the bandwidth, the scattered pilot pattern and the FFT sizes. A set of the allowed combinations for GI and 6 MHz bandwidth is shown in Table 2.

GI (µs)	FFT Size			Samples
	8k	16k	32k	
27.87	✓	✓	✓	192
55.56	✓	✓	✓	384
74.07	✓	✓	✓	512
111.11	✓	✓	✓	768
148.15	✓	✓	✓	1024
222.22	✓	✓	✓	1536
296.30	✓	✓	✓	2048
351.85	✓	✓	✓	2432
444.4	N/A	✓	✓	3072
527.78	N/A	✓	✓	3648
592.59	N/A	✓	✓	4096
703.70	N/A	N/A	✓	4864

Table 2. GI v FFT size combinations

Based on the previous description, an example of the ATSC 3.0 frame structure is given in Figure 6.

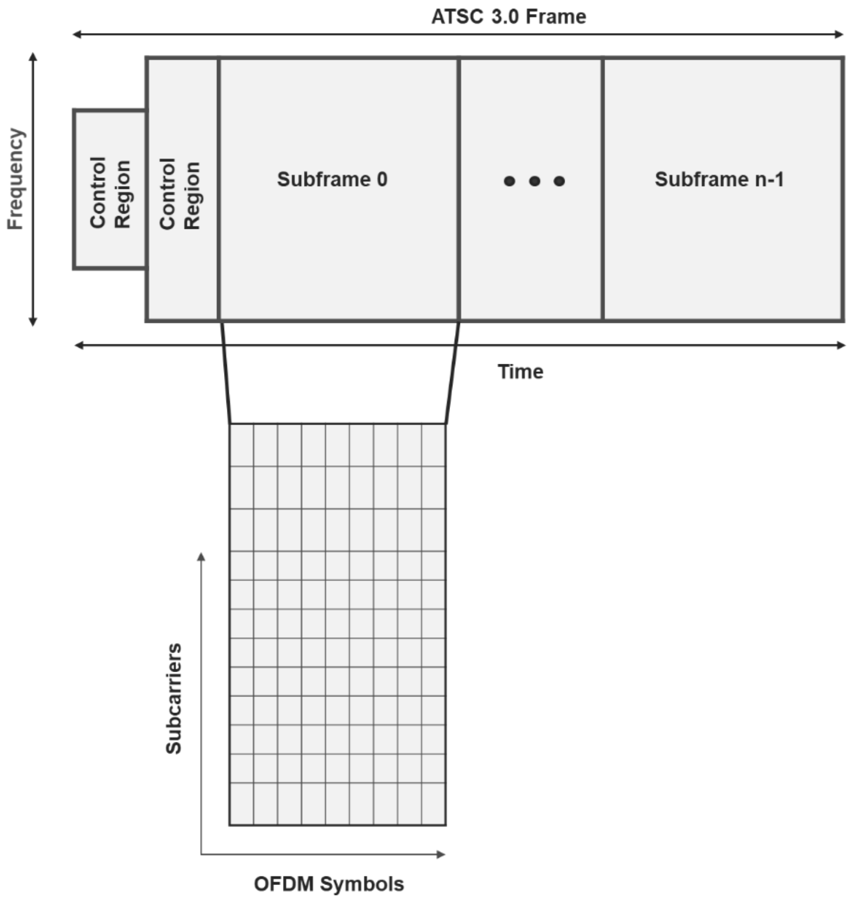

Figure 6. ATSC 3.0 Frame Structure.

Within the described frame structure, three time multiplexed regions are defined depending on the allocated content:

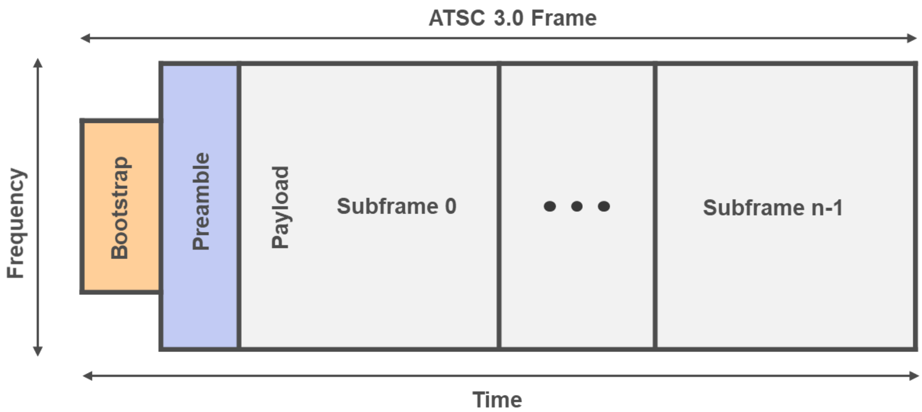

Figure 7. ATSC 3.0 frame regions.

- **Bootstrap:** Control region that contains basic signalling information needed by the receivers to enable the synchronization and demodulation of the rest of the frame. It also conveys some additional information such as ATSC 3.0 standard version, system bandwidth, sampling rate and preamble structure. Bootstrap is located at the beginning of each frame and is composed of several OFDM symbols. The first OFDM symbol is used for synchronization while the rest are used to carry all the additional information. Bootstrap is coded with extremely robust techniques to facilitate the reception under extremely bad conditions for all the devices.

- **Preamble:** Second control region that contains specific Layer 1 (L1) signalling information required to access the payload. It is located immediately after the bootstrap and is composed of two different parts, L1-Basic and L1-Detailed. While the former provides signalling information used to access the L1-Detailed part, the latter provides all the information required to access the payload. Both parts are distributed along one or more OFDM symbols, which can be transmitted with different waveform parameters.

- **Payload:** Contains all the data and reference signals transmitted in a frame. The content can be distributed in one or more subframes, which are located after the preamble. Each subframe has a fixed waveform configuration and different subframes may have different configurations along the same ATSC 3.0 frame. Data is allocated in all subcarriers and OFDM symbols available. Regarding reference signals, different types are inserted across the rest of time and frequency positions depending on the pilot pattern:

  - **Scattered Pilots (SP):** Used to estimate the channel in time and frequency domains. SP are distributed by means of different SP patterns defined by the parameters D_x and D_y. D_x, specifies the separation of pilot bearing carriers along different OFDM symbols in frequency domain, and D_y specifies the separation of pilot bearing carriers for the same subcarrier in time domain.

  - **Continual Pilots (CP)** and **Edge Pilots**: Used for synchronization, transmission mode identification and phase noise tracking. CP and Edge Pilots are inserted in fixed subcarrier positions for all OFDM symbols.

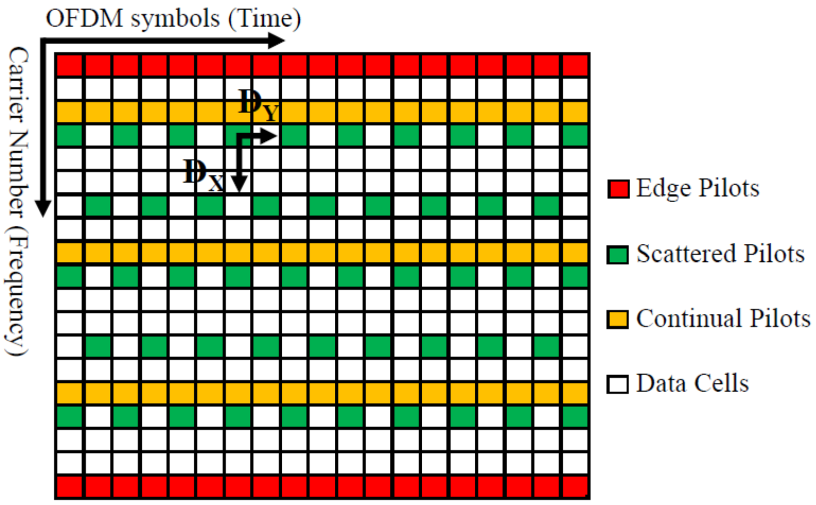

Figure 8. ATSC 3.0 pilot distribution.

3.3 LTE eMBMS

LTE is considered as the most efficient PTP communication system for delivering content in cellular deployments. Despite LTE is based generally on PTP capabilities, several PTM features have also been included in different releases since the beginning of the standardization process. The design of all LTE releases follows a backwards compatible philosophy [7].

LTE introduced the first LTE PTM technological approach, enhanced Multimedia Broadcast Multimedia Service in Release 9. eMBMS Rel.9 enabled broadcast transmissions thanks to the inclusion of a new dedicated multicast channel and a SFN operation mode. This mode, which was envisaged as MBSFN, was able to deliver unicast and broadcast popular content to large amounts of users in large size areas. By using SFNs, MBSFN obtained high performance gains in comparison to traditional systems by delivering the same content with the same operation frequency through time synchronized transmissions. MBSFN was specially valued as a good solution to deliver broadcast services through the cellular network in HPHT scenarios, e.g. in TV reception on mobile phone.

Release 12 introduced MooD, which allowed to activate and deactivate MBMS services in an automatic and seamless way depending on the User Equipment (UE) service consumption. MooD is performed on higher layers and is transparent for the physical layer.

In Release 13, Single-Cell PTM was introduced as a flexible unicast and multicast/broadcast solution that allowed to deliver the same content to groups of users within a single cell. To enable that, SC-PTM reused most of the unicast physical channels, obtaining a flexible and scalable design that enabled to transmit unicast or multicast/broadcast content depending on the number of users interested in the same service within the cell. SC-PTM is considered as a good solution to deliver broadcast services through the cellular network in small cell scenarios, i.e. LPLT scenarios.

Release 14 introduced the current PTM state-of-the-art, LTE eMBMS Release 14. As main novelty, Release 14 allowed to deliver unicast and broadcast services for different use cases, e.g. V2X, SC-PTM, NB-IoT, in small and large scale scenarios. Release 14 also introduced a mode to enable the distribution of TV services for fixed and mobile receivers in an efficient way. This mode**,** which was envisaged as LTE enhanced TV (LTE enTV), supported TV reception in a common spectrum allocation together with the delivery of high quality content and operation according the EU regulation on 470-790 MHz frequency spectrum. To achieve that, LTE included several enhancements over the architecture, service and radio layer in order to allow TV broadcasters to build on their existing TV broadcast service infrastructure.

Regarding the architecture, Rel.14 included the use of two interfaces: MBMS-API, which is used from the MBMS client to the Content Receiver application, and xMB interface, used from the content provider to the BM-SC to transmit unicast or broadcast by using MooD.

For the service layer, Transport-only Mode was defined as a solution to enable the distribution of IP packets and UDP data flows over MBMS bearers. In addition, Receive-only Mode (ROM) was also included as one feature to enable devices to receive MBMS services without the use of a SIM card. This mechanism allowed to integrate traditional TV receivers in the new MBMS system.

Finally, some physical layer enhancements were integrated to enable the deployment of dedicated TV broadcast infrastructures supporting public broadcasting requirements. Among other features, LTE enTV allowed to cover larger areas through large scale SFN deployments thanks to the definition of new subcarrier spacings (SCS) and CP values. Since the TFM scope is focused on the physical layer analysis, the following subsections provide a detailed description about the current LTE eMBMS physical layer design, including an evaluation of the current frame structure, the physical channel allocation and the transmission block chain [8].

3.3.1 eMBMS Frame Structure

LTE eMBMS reuses the traditional LTE frame structure. LTE technology conveys control and data information in LTE frames with a total duration of 10 ms. Each frame is composed of 10 subframes, where each subframe has a fixed duration of 1 ms and contains two slots. Each slot has a duration of 0.5 ms and is composed of different OFDM symbols in the time domain, whose number depends on the subcarrier spacing and the CP type. In the frequency domain, one slot may contain a variable number of subcarriers depending on the available bandwidth and subcarrier spacing. LTE offers the possibility of selecting different bandwidth values for a RF carrier: 1.4, 3, 5, 10 15 and 20 MHz, where, as maximum, 5 carriers can be aggregated. Regarding subcarrier spacing, 15 kHz is the only value allowed.

The resource allocation in time and frequency is performed at the resource grid by defining different framing units. The smallest framing unit is defined as Resource Element (RE), which is equivalent to 1 subcarrier allocated in 1 OFDM symbol. Based on that, a group of 12 subcarriers per 7 OFDM symbols is defined as a Resource Block (RB). Each slot can contain between 6 and 110 RB depending on the available system bandwidth. According to this, an example of the LTE frame structure is shown in Figure 9.

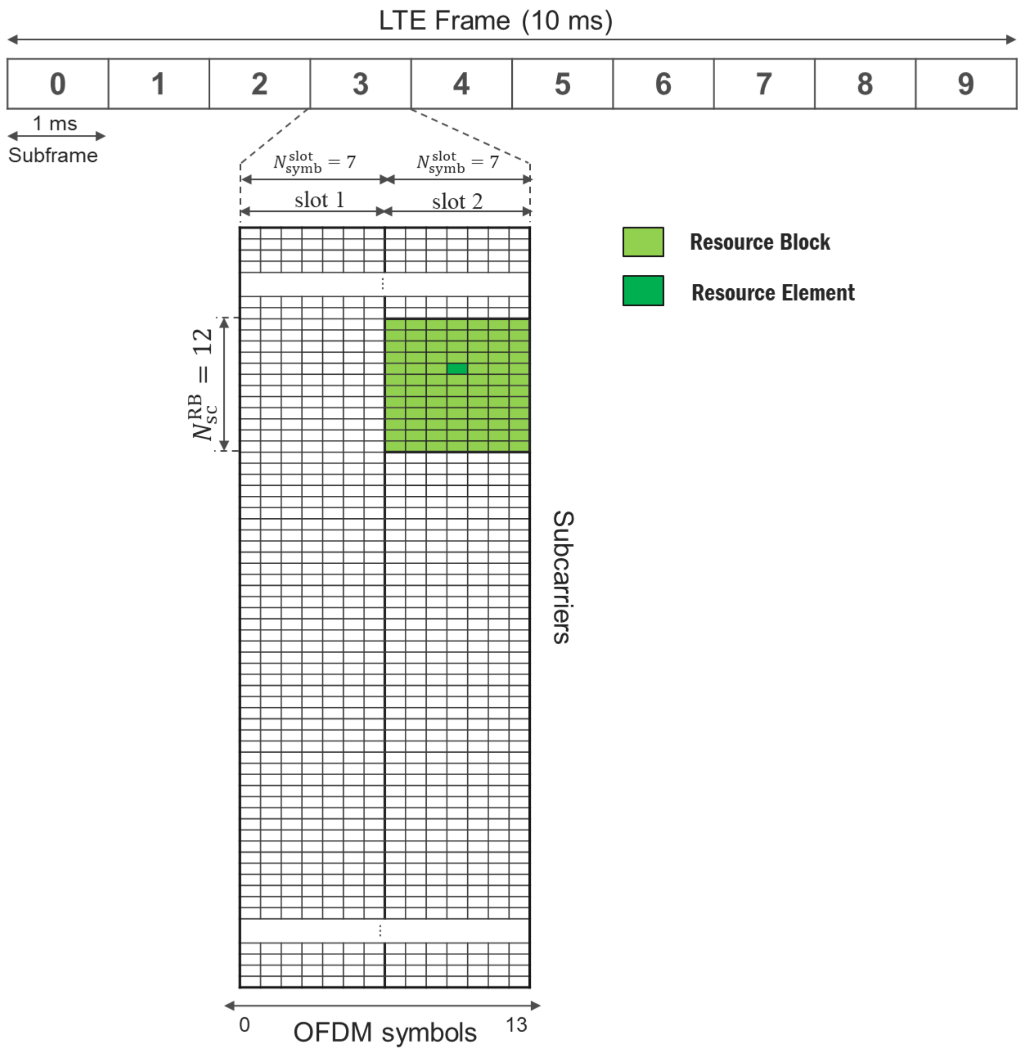

Figure 9. LTE Frame structure.

Based on the previous frame structure, LTE enTV introduces some physical layer modifications to enhance SFN transmissions. Regarding subcarrier spacings, LTE enTV keeps the traditional value, 15 kHz, and introduces two more possible values: 7.5 kHz and 1.25 kHz. The decrease of the subcarrier spacing implies the definition of longer CP values. Longer cyclic prefixes imply larger coverage and ISD in SFN environments since robustness against multipath is improved. As shown in Table 3, eMBMS allows two different CP configurations, Normal CP and Extended CP, that combined with the different spacing values, enable four different CP lengths.

SCS (kHz)	CP Type	CP Length (µs)
15	Normal	4.7/5.2
	Extended	16.67
7.5	Normal	33.33
1.25	Normal	200

Table 3. LTE eMBMS Cyclic Prefix configurations

Apart from cyclic prefix, narrower subcarrier spacing implies larger useful OFDM symbol. As a consequence, a lower number of OFDM symbols is needed to fulfil a LTE subframe.

3.3.2 LTE eMBMS Physical Channels and Signals

LTE eMBMS Rel. 14 allows to multiplex unicast and broadcast services in a flexible way across the same frequency carrier. Broadcast content can be allocated from the 0% up to 100% of the total amount of resources. Depending on the broadcast occupation, unicast and broadcast services can be multiplexed in the frame structure through two different approaches:

- **Unicast and broadcast TDD multiplexing:** When broadcast content occupies between 0% and 80% of the total frame, unicast and broadcast services can be multiplexed in time domain. TDD multiplexing is performed by allocating both services in different subframes as shown in Figure 10.

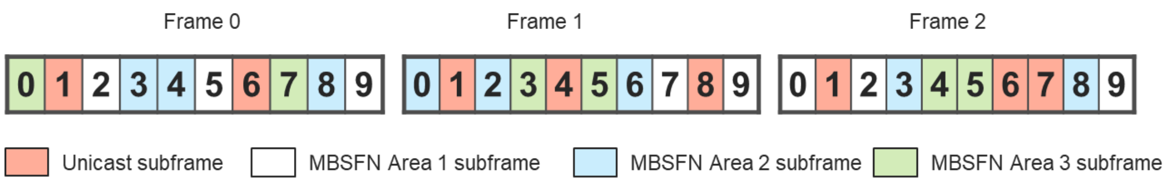

Figure 10. Unicast and broadcast TDD multiplexing.

- **Full Broadcast allocation:** LTE eMBMS Rel. 14 also introduces the possibility to perform nearly a 100% broadcast allocation in a LTE frame. This allocation can only be performed when subcarrier spacing 1.25 kHz is selected. To enable the 100% broadcast allocation, eMBMS subframes without unicast control region are transmitted. However, in order to transmit the required signalling information, a unicast subframe, i.e. Cell Acquisition Subframes (CAS) is transmitted in 1 of each 40 subframes. An example of the LTE frame structure for 100% broadcast transmissions is shown in Figure 11.

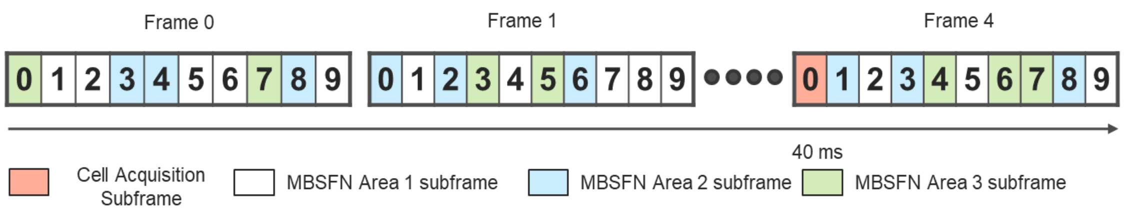

Figure 11. Full broadcast allocation.

Based on both approaches, a description of the physical channels and signals allocated in unicast and broadcast subframes is given next.

Unicast Subframes

On the one hand, unicast subframes convey services over the traditional LTE physical channels. LTE unicast physical channels are used to provide initial access, control and data content in downlink and uplink transmissions. Since the scope of this study is mainly focused on broadcast transmissions, only the allocation and functionality of the downlink physical channels and signals is described:

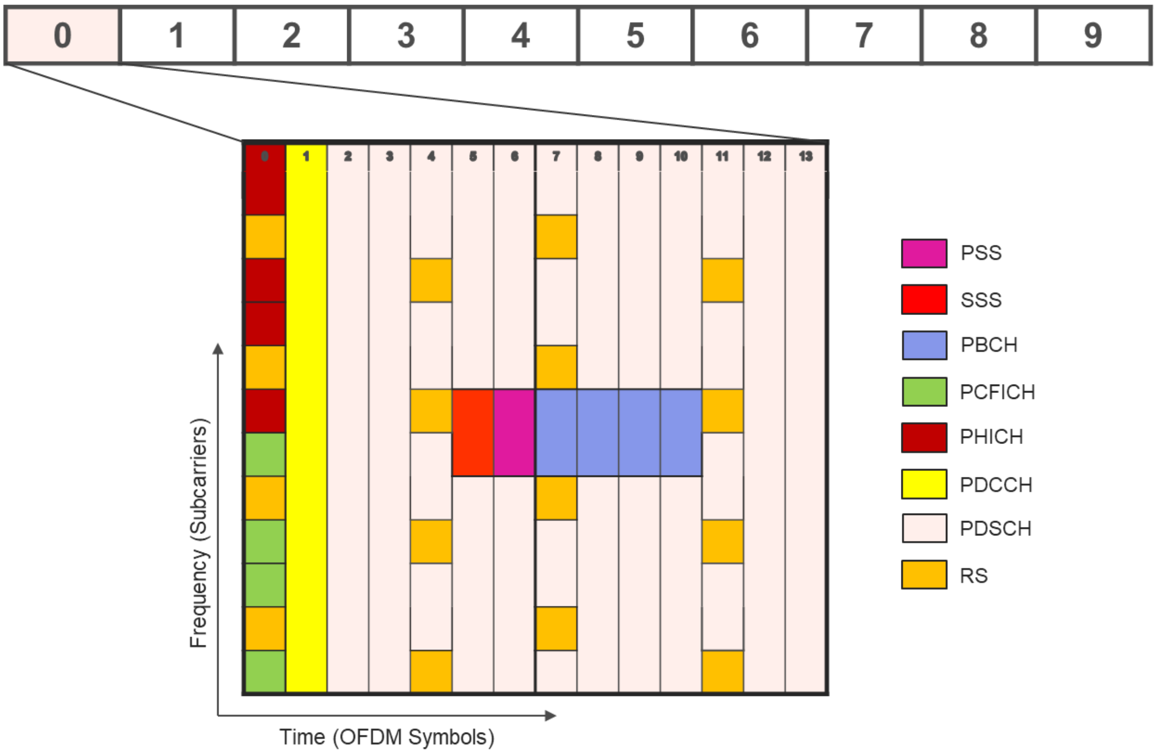

Figure 12. LTE unicast physical channel allocation.

- **Physical Broadcast Channel (PBCH):** Downlink channel used to convey the Master Information Block (MIB). MIB is a set of bits that specifies all the required information to perform the initial access of the cell, i.e. downlink system bandwidth, the Physical Hybrid ARQ Indicator Channel (PHICH) structure, part of the System Frame Number, etc. PBCH information is distributed across the first four OFDM symbols of the slot 1 for each LTE frame.
- **Primary and Secondary Synchronization Signals (PSS and SSS):** Physical signals used to enable UE synchronization at the subframe level. PSS are used to enable the slot timing detection as well as to provide the Physical Layer ID. PSS are mapped in the sixth OFDM symbol of the slot 0 and 10. SSS are used to obtain the physical layer cell identity group, which is required to enable the radio frame timing detection as well as the cyclic prefix length detection, among others. SSS are located at the fifth OFDM symbol of the slot 0 and 10.
- **Physical Control Format Indicator Channel (PCFICH):** Physical channel that conveys he Control Format Indicator (CFI). CFI is a set of bits that informs about the number of OFDM symbols transmitted at the PDCCH. PCFICH is located at the first OFDM symbol of each subframe. PCFICH REs are grouped in four different resource element groups (REG) that are spread across the whole frequency domain.
- **Physical Hybrid-ARQ Indicator Channel (PHICH):** Physical channel that carries positive or negative acknowledgements (ACK/NACKs) related to uplink data transmissions done on the Physical Uplink Shared Channel (PUSCH). If normal CP is used, PHICH is conveyed in

the first OFDM symbol, while if extended CP is used, PHICH is conveyed in the three first OFDM symbols.

- **Physical Downlink Control Channel (PDCCH):** Physical channel used to transmit the Downlink Control Information (DCI). DCI is a set of bits used to provide information about the resource allocation and the parameter configuration transmitted in the DL-SCH, UL-SCH and PCH. Depending on its functionality, different DCI formats can be defined. PDCCH content is transmitted at the beginning of each subframe and it is spread in 1, 2 or 3 OFDM symbols, depending on the PHICH.
- **Physical Downlink Shared Channel (PDSCH):** Physical channel used to transmit System Information Blocks (SIBs), paging, RRC signalling messages and data information. PDSCH content is allocated in all the resource grid positions where the rest of the physical channels are not allocated. PDSCH information can be modulated with QPSK, 16QAM, 64QAM or 256QAM.
- **Reference Signals:** Depending on its functionality different types of reference signals are defined:
    - **Cell-specific Reference Signals (CRS):** Reference signals used to enable the cell search and initial acquisition as well as the downlink channel estimation for all UEs. They are allocated in PDSCH positions, depending on different patterns and antenna port configurations.
    - **UE-specific Reference Signals:** Reference signals used to enable PDSCH demodulation for specific UEs. It can be used for enabling UE beamforming.
    - **Channel-State Information Reference Signals (CSI-RS):** Reference signals used to report Channel Quality Indicators (CQIs). They are allocated in sparse positions in time and frequency domain.

eMBMS Subframes

On the other hand, eMBMS subframes convey specific physical channels in order to transmit control and data broadcast information. The information corresponds to specific MBMS services in a eMBMS area. Physical channels and signals are allocated in eMBMS subframes as shown in Figure 13.

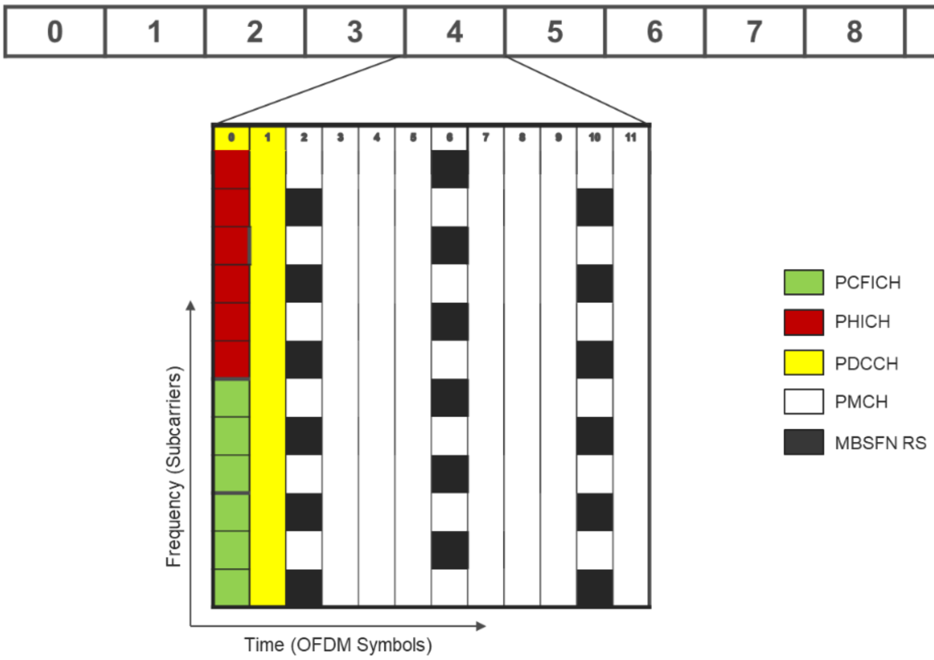

Figure 13. LTE eMBMS Rel. 14 physical channel allocation.

- **Physical Multicast Channel (PMCH):** Specific physical channel used to convey broadcast data in eMBMS subframes. PMCH was introduced in LTE Release 9, when broadcast capabilities were included in LTE technology (eMBMS MBSFN). PMCH substitutes PDSCH as physical channel to convey data. The inclusion of PMCH enables the introduction of new numerologies (7.5 kHz and 1.25 kHz) and eMBMS pilot patterns into the physical layer design in order to provide a more suitable solution for SFN deployments. PMCH design does not allow MIMO transmissions.
- **MBSFN Reference Signals:** Specific reference signal design optimized to enable SFN transmissions. MBSFN reference signals are transmitted in antenna port number 4. As for ATSC 3.0, reference signals allocation is given by pilot patterns, which are defined by the frequency (D_x) and time position (D_y). Depending on the subcarrier spacing and the CP type, LTE eMBMS Rel. 14 defines different MBSFN pilot patterns:
    - **Subcarrier Spacing 15 kHz and normal CP:** Reference Signals (RS) are inserted in same time and frequency positions than unicast. Regarding time domain, RS are allocated in OFDM symbols number 0, 4, 7 and 11 for each subframe. In frequency domain, RS are inserted in subframes positions depending on Physical Cell ID and other parameters.
    - **Subcarrier Spacing 15 kHz and extended CP:** Since the use of extended CP reduces the number of OFDM symbols to 12 symbols, RS time domain allocation changes. RS are allocated in different subcarriers for OFDM symbols number 2, 6 and 10.

- **Subcarrier Spacing 7.5 kHz:** With 6 OFDM symbols occupying the subframe, RS are inserted in different frequency positions every four subcarriers for OFDM symbols number 1, 3 and 5.
- **Subcarrier Spacing 1.25 kHz**: eMBMS subframe is occupied by one OFDM symbol. As a consequence, RS are transmitted every six subcarriers during the whole time domain. Subcarrier positions are frequency shifted depending on the subframe index.

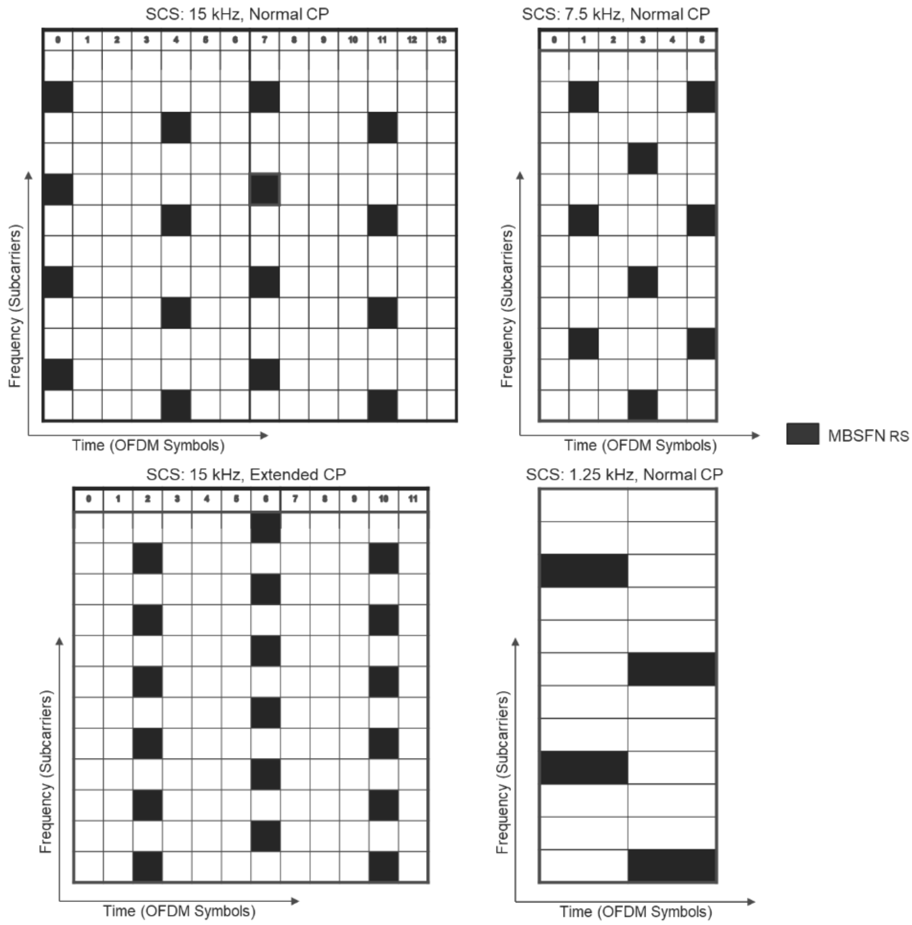

Figure 14. MBSFN Reference Signal allocation.

- **Unicast control region:** Despite the definition of a new broadcast channel, eMBMS subframes convey control and signalling information in the traditional unicast channels, i.e. PDCCH, PCFICH and PHICH. Depending on the selected subcarrier spacing, unicast control region can be allocated through two different approaches:
  - **Traditional control region:** When 15 kHz or 7.5 kHz subcarrier spacing is selected, control information is allocated in the same unicast control region, i.e. over the first, two or three OFDM symbols of each eMBMS subframe. This configuration allows to keep the backwards compatibility with previous releases.
  - **Cell acquisition subframe:** When 1.25 kHz subcarrier spacing is selected, control content is transmitted in 1 of each 40 subcarriers. CAS conveys PSS, SSS,

PBCH, PDCCH and PDSCH and is configured with unicast numerology, i.e. 15 kHz, and normal or extended cyclic prefix. Due to the reuse of unicast numerology, the inclusion of CAS may limit the LTE enTV coverage in SFN environments.

Chapter 4. Point-to-Multipoint Gap Analysis.

The growth in the delivery of traditional multicast/broadcast content together with the appearance of new services such as IoT or V2X has established the need of developing a multicast/broadcast solution able to cover all the different use cases. Related to that, 3GPP has defined in [3] a list of multicast/broadcast requirements that need to be fulfilled by the new PTM solution.

Part of these requirements are related to the need of developing a broadcast solution able to deliver traditional TV content in HPHT scenarios. This solution has been addressed as terrestrial broadcast. Since the latest version of eMBMS Rel.14 includes a dedicated terrestrial broadcast solution, i.e. LTE enTV, 3GPP has approved the creation of a new Work Item for Release 16 in order to evaluate if the enTV capabilities are able to meet the new 3GPP PTM requirements. This evaluation, which is known as gap analysis, will analyse all the LTE enTV features related to the 3GPP requirements. If all the requirements are fulfilled, it will not be necessary to design a new 5G NR broadcast solution.

Motivated by this and aligned with the objective of this study, the current section performs a gap analysis where LTE enTV and ATSC 3.0 have been considered as a reference to determine if a new terrestrial broadcast solution has to be defined. Following the methodology specified in Chapter 2, the gap analysis is only performed at physical layer level.

4.1 3GPP Requirements

First, this subsection provides a detailed description of all the 3GPP requirements defined at [3]. To that end, the set of requirements has been described and subsequently classified as relevant or non-relevant for the design and evaluation of the new terrestrial broadcast solution. The classification of both categories is described in Chapter 2. According to them, the list of requirements is enumerated and classified as follows:

R1: PTM solution shall allow to deliver the existing multicast/broadcast services (e.g. TV, streaming, group communications, etc.) and new services (e.g. IoT, V2X, etc.)

This generic requirement is directly related with the design of a terrestrial broadcast solution for the delivery of traditional TV services (among others). As a consequence, it has been considered as relevant for the present study.

R2: PTM solution shall allow to adjust dynamically the multicast/broadcast service area depending on the service requirements, user distribution, etc.

To enable the diffusion of regional services in specific MBMS areas, the new terrestrial broadcast solution shall fulfil this requirement. In order to allow changes in the service area size, a flexible and scalable physical layer design with different CP lengths and transmitter configurations is required. According to this, this requirement is considered as relevant.

R3: PTM solution shall allow the concurrent delivery of unicast and multicast/broadcast services to all users.

From the generic scope, the UE should be able to receive unicast and multicast/services simultaneously, being both services allocated in different carriers. However, this study is focused on the design of terrestrial broadcast solution for the delivery of traditional TV content in a single carrier (100% multicast/broadcast). Therefore, this requirement is considered out of the scope and non-relevant.

R4: PTM solution shall allow the multiplexing of unicast and multicast/broadcast in time and frequency domain.

Based on the previous reasoning, since this study is intended to allocate 100% multicast/broadcast content in a single carrier, the multiplexing with unicast services is considered out of scope.

R5: PTM solution shall allow static and dynamic resource allocation between unicast and multicast/broadcast services, where multicast/broadcast resources shall be allocated from 0% up to the 100% (downlink-only mode with one or more MBMS dedicated carrier).

To enable the allocation of 100% of resources to multicast/broadcast services, the design of specific multicast/broadcast physical channels and signals together with a control region to convey the signalling is required. The design of these channels and specially the new control region may have an impact on the physical layer design. As a consequence, this requirement is considered as relevant for the project.

R6: PTM solution shall support multicast/broadcast network sharing between mobile network operators. The case of a dedicated MBMS network is also considered.

Despite this requirement is directly related to the design of a terrestrial broadcast solution, the design of network sharing capabilities is based on the design of new interfaces at the RAN architecture layer and it is not related with the physical layer. As a consequence, this requirement is considered as not relevant.

R7: PTM solution shall include a SFN operation mode to cover large geographical areas up the size of a country and also cells with up to 100 km of radius shall be created. Local, regional and national broadcast areas shall also be possible.

The design of a SFN operation mode for a new terrestrial broadcast solution in HPHT scenarios is the main objective of this master thesis. To enable SFN capabilities for different coverage ranges, a specific physical layer design, including scalable and large CP values, is required. This requirement is fully aligned with the current study and therefore it is considered as relevant.

R8: PTM solution shall be able to deliver content to UE with high spectral efficiency in fixed, portable and mobile conditions. Speeds up to 250 km/h shall be supported.

To enable different mobility conditions in the new terrestrial broadcast solution, a scalable and flexible physical layer design is needed. The use of narrow subcarrier spacings allows to provide large coverage due to the definition of large CPs. However, this SCS values are very vulnerable to Doppler effects. As a consequence, there exists a trade-off between CP length and mobility that may have an impact on the physical layer design. Based on that, this requirement is considered as relevant for this master thesis.

R9: PTM solution shall enable the use of different types of hardware and software, e.g. MIMO, to improve multicast/broadcast capacity and reliability.

Since MIMO configuration can improve multicast/broadcast capacity and reliability, the inclusion of MIMO techniques in the physical layer may enhance the potential terrestrial broadcast mode. Therefore, this requirement is considered as relevant for the present study.

R10: PTM solution shall support multicast/broadcast services for mMTC devices.

Terrestrial broadcast is focused on the delivery of traditional TV services where large bandwidths are required to deliver high quality content. Since mMTC requires of different features to deliver small data content, this requirement is considered out of scope.

Based on this analysis, Table 4 summarizes the classification of the list of requirements:

Requirements	Relevant	Non-relevant
R1	X	
R2	X	
R3		X
R4		X
R5	X	
R6		X
R7	X	
R8	X	
R9	X	
R10		X

Table 4. Classification of 3GPP requirements.

4.2 Gap Analysis

This subsection analyses the selected requirements for the terrestrial broadcast evaluation. To that end, ATSC 3.0 and LTE eMBMS have been considered as technological references. Due to the flexibility of the considered broadcast solutions, it is assumed that all the requirements do not have to be fulfilled at the same time by means of the same physical layer configuration. The set of requirements has been evaluated through the two methodologies defined in Chapter 2.

R1: PTM solution shall allow to deliver the existing multicast/broadcast services (e.g. TV, streaming, group communications, etc.) and new services (e.g. IoT, V2X, etc.)

R1 is directly related with the design of a new multicast/broadcast solution for the delivery of traditional TV services over the mobile network. By inspection, the existence of a terrestrial broadcast mode in ATSC 3.0 and eMBMS Rel.14 has been investigated.

On the one hand, ATSC 3.0 is defined as the next-generation terrestrial broadcast solution, being able to deliver DTT content. ATSC 3.0 physical layer was designed to provide high system capacity to deliver UHD TV services, robust transmissions, improved efficiency and many other features that enable the simultaneous reception for fixed and mobile devices [9]. However, ATSC 3.0 is a terrestrial broadcast solution that reuses the existing DTT architecture and it is not compatible with the 3GPP backwards philosophy. In addition, the deployment of an ATSC 3.0 solution in cellular environments is not efficient energetically and economically. As a consequence, ATSC 3.0 cannot be considered as a valid solution for delivering broadcast content through the existing cellular network.

On the other hand, as explained in Chapter 3 LTE enTV enables the efficient distribution of TV services thanks to the introduction of different mechanisms at architecture, service and physical layers. LTE enTV allows to provide mobile and fixed TV reception, free-to-air services and same quality levels than traditional broadcast systems [10].

R2: PTM solution shall allow to adjust dynamically the multicast/broadcast service area depending on the service requirements, user distribution, etc.

To enable the dynamic adjustment of the multicast/broadcast service area, physical layer solution shall include scalability and granularity in order to define different CP lengths, transmitter configurations, etc. The presence of these characteristics has been analysed by inspection.

As showed in Table 2, ATSC 3.0 includes a set of twelve possible GI values depending on the FFT size and bandwidth configuration. For 6 MHz bandwidth, GI values cover ranges from 28 µs to 700 µs. This granular selection may enable to configure different coverage areas for non-SFN and SFN deployments depending on the user distribution, the service requirements, etc.

According to Table 3, LTE enTV defines four possible CP values depending on the selected SCS, reaching values from 4.7 µs to 200 µs. As it can be observed, even though LTE enTV granularity is lower than ATSC 3.0, Rel.14 is also able to provide different CP lengths and therefore different service area sizes for non-SFN and SFN deployments.

R5: PTM solution shall allow static and dynamic resource allocation between unicast and multicast/broadcast services, where multicast/broadcast resources shall be allocated from 0% up to the 100% (downlink-only mode with one or more MBMS dedicated carrier).

The design of a specific multicast/broadcast physical channel together with the insertion of a control region is needed in order to allocate multicast/broadcast resources at the 100% of the MBMS dedicated carrier. This requirement has also been analysed through inspection.

As mentioned previously, ATSC 3.0 is considered a specific solution designed to deliver traditional TV content to all users. To achieve that, a 100% multicast/broadcast resource allocation is performed. As shown in Chapter 3, ATSC 3.0 frame structure and resource allocation were designed to fulfil the downlink only mode requirement. According to this, signalling and data information is transmitted to all UEs by allocating the 100% of resources across the bootstrap, the preamble and the payload.

LTE enTV enables a nearly 100% resource allocation to multicast/broadcast services in one or more dedicated eMBMS carrier for the MBSFN operation mode. To enable this 100% allocation, LTE enTV transmits all the data resources in an SFN fashion over the PMCH channel, a multicast/broadcast dedicated channel. Regarding control information, LTE enTV defines a specific and small control region to convey the signalling information. SCS 15 kHz and 7.5 kHz modes convey the same unicast control region used to deliver unicast service. On its behalf, SCS 1.25 kHz mode defines a periodic control region named CAS, which is sent in 1 of each 40 subframes. CAS are non-multicast/broadcast subframes transmitted over a unicast-based numerology. Even though this, LTE enTV is considered to allow a nearly full 100% allocation to multicast/broadcast services. The design of smaller multicast/broadcast control regions for the new PTM solution could be considered as one of the aspects to investigate in future analysis.

R7: PTM solution shall include a SFN operation mode to cover large geographical areas up the size of a country and also cells with up to 100 km of radius shall be created. Local, regional and national broadcast areas shall also be possible.

In SFN scenarios, CP provides the maximum echo delay tolerance for echoes arriving from the further transmitter. Based on this parameter, the maximum ISD between transmitters in a SFN scenario can be calculated. Considering this relation, to enable the design of a SFN operation mode with different coverage area options, different CP values have to be included at the terrestrial broadcast physical layer solution. The calculation of the ISD associated to the CP values has been obtained through a mathematical analysis.

As shown in Table 2, ATSC 3.0 physical layer offers twelve possible GI values expressed in in time duration (µs). GI values can be converted into ISDs values for SFN scenarios by means of the following expression:

$$ISD\ (km) = \frac{c\left(\frac{m}{s}\right) \times GI(s)}{1000} \tag{1}$$

where c is defined as the light speed and GI as the guard interval length. According to it, the ISD values obtained for ATSC 3.0 are shown in Table 5:

GI (µs)	ISD (km)
27.87	8.36
55.56	16.67

74.07	22.22
111.11	33.33
148.15	44.44
222.22	66.66
296.30	88.89
351.85	105.55
444.4	133.33
527.78	158.33
592.59	177.77
703.70	211.11

Table 5. Relation between GI and ISDs for ATSC 3.0

As it can be observed, ATSC 3.0 offers a wide granularity of ISDs and fulfils the requirement of covering cells with a radius of 100 km.

Regarding LTE eMBMS, four different CP values can be configured depending on the selected SCS (see Table 3). It should be noted that for narrower SCS values, longer CP values are obtained. Following Equation 1, the correspondence between CP values and ISDs is given as follows:

SCS (kHz)	CP Type	CP Length (μs)	ISD (km)
15	Normal	4.7/5.2	1.4
	Extended	16.67	5
7.5	Normal	33.33	10
1.25	Normal	200	60

Table 6. Relation between CP and ISD for LTE enTV

As shown in Table 6, LTE enTV offers a maximum ISD value of 60 km for SCS 1.25 kHz in SFN scenarios. It should be noted that this SCS configuration can be only applied to the PMCH data region. Regarding control region, only SCS 15 kHz can be configured for control region and CAS, and consequently, only ISD = 5 km can be achieved. This aspect has been analysed in studies like [11], demonstrating that the presence of CAS may limit LTE enTV coverage. Based on these conclusions, it can be assured that LTE enTV does not fulfil R7.

R8: PTM solution shall be able to deliver content to UE with high spectral efficiency in fixed, portable and mobile conditions. Speeds up to 250 km/h shall be supported.

Mobility conditions are directly related to the Doppler effect, which depends on the system carrier frequency. The maximum mobility value is given by the maximum frequency shift, i.e. Doppler shift, allowed in the system:

$$f_D = \frac{v \cdot f_c \cdot cos\alpha}{c} \quad (2)$$

being c the speed of light, v the receiver velocity, f_c the frequency of the signal, and α the angle between the receiver vector velocity and the arriving signal.

Based on this definition, the Doppler limit for a CP-OFDM waveform can be calculated as:

$$f_{D_{limit}} = \frac{1}{2 \cdot D_y \cdot (T_u + T_{cp})} \quad (3)$$

where Dy is the separation between reference signals in the time domain and $T_u + T_{cp}$ and is the total OFDM symbol duration calculated as the sum between the CP duration and the useful OFDM symbol duration.

Equation 3 shows how mobility depends on different system factors as the pilot pattern, the SCS, the frequency of operation and the system bandwidth. Narrow SCS provide large OFDM symbol and CP durations. As a consequence, low Doppler limits and low tolerance to mobility conditions are obtained. Since LTE enTV and ATSC 3.0 include the use of different SCS and RS patterns, the mobility tolerance for both configurations has been analysed.

LTE eMBMS includes four possible SCS and CP configurations: 15 kHz with Normal CP, 15 kHz with Extended CP, 7.5 kHz and 1.25 kHz. For these configurations, three possible D_y values are defined. Based on this, the maximum Doppler limit and the theoretical mobility tolerance has been calculated in Table 7:

SCS (kHz)	Tu (μs)	CP (μs)	D_y	Maximum Fd (Hz)	Maximum Speed for 700 MHz (Km/h)
15	66,66	5.2	8	869.74	1341.89
	66,66	16.66	8	750.12	1157.19
7.5	133,33	33.33	4	750.03	1157.19
1.25	800	200	2	250	385.71

Table 7. LTE eMBMS mobility tolerance

As it can be seen, LTE eMBMS meets the mobility requirement thanks to the use of an accurate RS pattern design. D_y values are decreased for narrow SCS in order to provide a proper channel estimation in mobility conditions. However, the performance of the system is also directly influenced by the transmission mode. Some studies like [11] have demonstrated through link-level simulations that LTE eMBMS with SCS 1.25 kHz cannot provide a good performance for speeds higher than 100 km/h at 700 MHz when high Modulation and Coding Schemes (MCS) are selected – See Annex A. As a consequence, it can be assured that not all the LTE eMBMS configurations meet the mobility requirement.

Regarding ATSC 3.0, a similar mobility evaluation has been performed in Table 8. ATSC 3.0 offers a fixed OFDM symbol length depending on the selected FFT size. Considering the most similar configuration to LTE eMBMS, i.e. FFT size = 8k, two different GI values have been analysed. In addition, the two only possible D_y values have also been considered.

Tu (µs)	CP (µs)	D_y	Maximum Fd (Hz)	Maximum Speed for 700 MHz (Km/h)
1185.18	55.56	2	201	310.11
		4	100.74	155.42
	296.29	2	168.75	260.35
		4	84.37	130.17

Table 8. ATSC 3.0 mobility tolerance

As it can be seen, the larger OFDM symbol duration and the longer CP configurations are the main limitation in the ATSC 3.0 mobility tolerance. In addition, similar analysis in [11] also show the influence of the transmission mode for the ATSC 3.0 mobility tolerance. According to this, it can be assured that ATSC 3.0 is not able to meet the 250 km/h requirement for all the possible configurations.

R9: PTM solution shall enable the use of different types of hardware and software, e.g. MIMO, to improve multicast/broadcast capacity and reliability.

The use of MIMO mechanisms like diversity techniques or spatial multiplexing improves the capacity and reliability of the system. However, not all technological solutions have a compatible physical layer design to enable MIMO configurations.

Regarding ATSC 3.0, MIMO transmissions with up to 2x2 antenna configurations are allowed in order to improve robustness and capacity be means of spatial diversity and multiplexing [12].

In relation to LTE enTV, MIMO configuration is not defined for the PMCH multicast/broadcast dedicated channel. As a consequence, only single antenna transmissions are allowed. In contrast, other LTE physical channels used to convey unicast transmissions, e.g. PDSCH, are able to transmit information through MIMO configurations. The reuse of the PDSCH could be studied in order to design a physical channel compatible with MIMO for the new terrestrial broadcast solution.

Based on this analysis, Table 9 summarizes the fulfilment of the set of requirements by both solutions:

Requirement	ATSC 3.0	LTE enTV
R1	X	✓
R2	✓	✓
R5	✓	✓
R7	✓	X
R8	✓	✓
R9	✓	X

Table 9. Fulfilled 3GPP requirements for ATSC 3.0 and LTE enTV

ATSC 3.0 is the most complete solution since it can be defined as a 100% terrestrial broadcast solution that provides a large CP granularity, large ISD in SFN scenarios (200 km. approx.) and the possibility transmit and receive content through MIMO configurations. However, ATSC 3.0 cannot be considered as a candidate solution since it is not designed for the delivery of multicast/broadcast services through the current cellular network. The use of a HPHT solution to deliver multimedia content in cellular environments is not efficient in terms of energy and costs. In addition, ATSC 3.0 can only fulfil the mobility requirement of speeds up to 250 km/h for a small set of configurations.

LTE enTV is the current state-of-the-art for terrestrial broadcast transmissions over the cellular network. It requires the transmission of a periodic unicast-based content, CAS, to convey the synchronization and control signalling. In addition, it offers a more limited CP granularity with four possible CP values. Regarding the ISD requirement, it is not able to reach the 100 km of coverage, providing values of up to 60 km. MIMO transmissions are not allowed since multi-antenna configurations are not defined for the PMCH. Finally, mobility requirement is only fulfilled for some specific configurations.

As a consequence, since ATSC 3.0 and LTE enTV are not able to fulfil all the 3GPP requirements, Chapter 5 studies the design of a 5G NR PTM solution to deliver terrestrial broadcast services.

Chapter 5: 5G New Radio

This section provides a description of the physical layer mechanisms introduced in the current PTP state-of-the-art, 5G NR. After that, and considering the PTP solution as a reference, a novel 5G NR Terrestrial Broadcast design has been proposed in order to meet the requirements 3GPP. The 5G Terrestrial Broadcast physical layer design has been proposed, analysed and subsequently evaluated following the same gap analysis procedure.

5.1 Point-to-Point State-of-the-Art: 5G NR Unicast.

5G New Radio is the current state-of-the art solution for PTP mobile communications. The new PTP standard, which was introduced in the latest version of Release 15, is defined as a new technology that offers flexibility, scalability and efficiency to fulfil the future connectivity requirements. With an unprecedented design, 5G is able to provide different services, such as enhance Mobile Broadband, Ultra Reliable Low Latency Communications, or massive Machine Type Communications (mMTC) for a wide frequency range (700 MHz – mm wave bands) with high performance, low cost and low power consumption [13].

To develop such an innovative solution, a flexible and forward compatible 5G NR air interface design, among other features, is needed. 5G NR air interface includes some of the most advanced physical layer mechanisms in order to provide high performance in cellular environments. The use of efficient encoding techniques such as LDPCs and polar codes, the inclusion of flexible and scalable numerologies and the use of massive MIMO are some of the new features included at the 5G solution [14] [15]. In order to analyse all these physical layer mechanisms, this subsection describes the 5G NR frame structure, and physical downlink channels and signals used to deliver 5G data content.

5.1.1 5G NR Frame Structure

5G NR transmits control and data information in 5G NR frames of 10 ms duration. Each frame is composed of 10 subframes, where each subframe lasts 1 ms. Due to the definition of different OFDM numerologies, each subframe can contain one or more slots. Each slot can convey several OFDM symbols depending on the selected CP type. On the one hand, if normal CP is selected, slots convey 14 OFDM symbols. On the other hand, 12 OFDM symbols are allocated for symbols with extended CP. The OFDM symbols transmitted in one slot are assigned to downlink or transmissions depending on the Slot Format Indicator (SFI). In frequency domain, each OFDM symbol contains a number of subcarriers depending on the available system bandwidth and numerology. 5G NR introduces a scalable numerology solution, defined by μ, a positive integer factor which has an impact on the subcarrier spacing, the OFDM symbol and cyclic prefix length. The influence of numerology in framing parameters is shown in Equations 4,5 and in Table 10.

$$T_u = \frac{1}{SCS} \tag{4}$$

$$SCS = 2^{\mu} \cdot 15\ kHz \tag{5}$$

where T_u is the useful OFDM symbol duration, SCS is the subcarrier spacing and μ is the numerology option.

μ	SCS (kHz)	Tu (μs)	Type CP	Tcp (μs)	Slot (μs)	Slots/subframe
0	15	66.66	Normal	5.2/4.7	1000	1
1	30	33.33	Normal	2.6/2.3	500	2
2	60	16.66	Normal	1.3/1.2	250	4
			Extended	4.16	250	4
3	120	8.33	Normal	0.65/0.59	125	8
4	240	4.17	Normal	0.33/0.29	62,5	16

Table 10. 5G NR numerology, OFDM symbol duration, CP type and slot distribution.

5G NR allows transmissions through different system bandwidths depending on the frequency range. Frequency Range 1 (FR1) is defined from 450 MHz to 6 GHz and allows system bandwidths of 5, 10, 15, 20, 25, 40, 50, 60, 80 or 100 MHz. Frequency Range 2 (FR2) is specified from 24.25 GHz to 52.6 GHz and enables bandwidths of 50, 100, 200 or 400 MHz.

The combination of one subcarrier allocated in one OFDM symbol is defined as one Resource Element. A group of 12 consecutive subcarriers in frequency domain is defined as Resource Block. Based on all these parameters, an illustrative example of the framing structure for numerology μ=0 is shown in Figure 15.

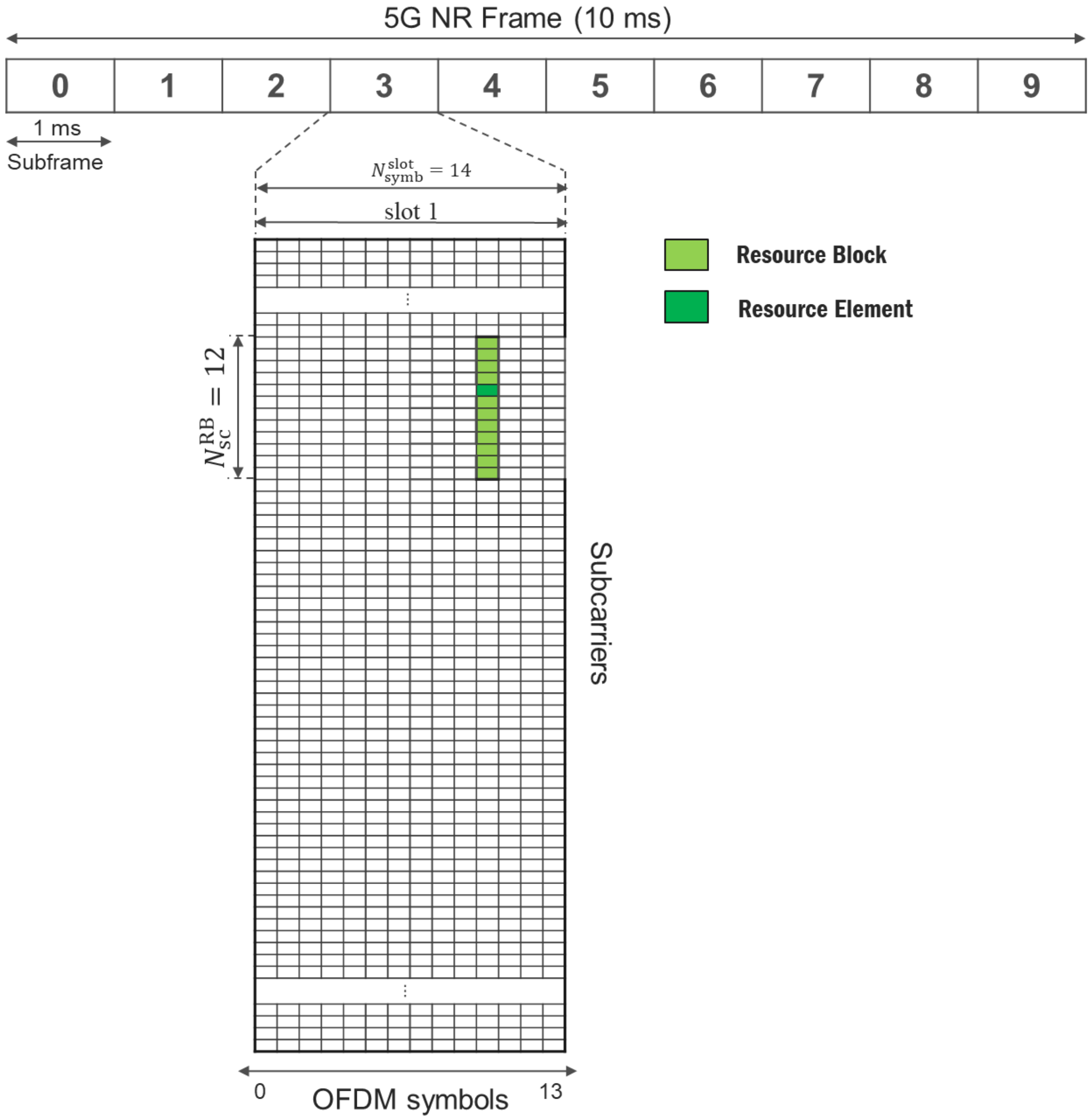

Figure 15. 5G NR Frame Structure.

5.1.2 5G NR Physical Channels and Signals

Control and data content is allocated at the described 5G NR frame structure for downlink and uplink transmissions thanks to the use of physical channels and signals. Since the scope of this master thesis is mainly focused on the downlink side, only the physical channels and signals transmitted from the base station (gNB) to the UE are described in this subsection. The set of downlink physical channels and signals is shown in Figure 16.

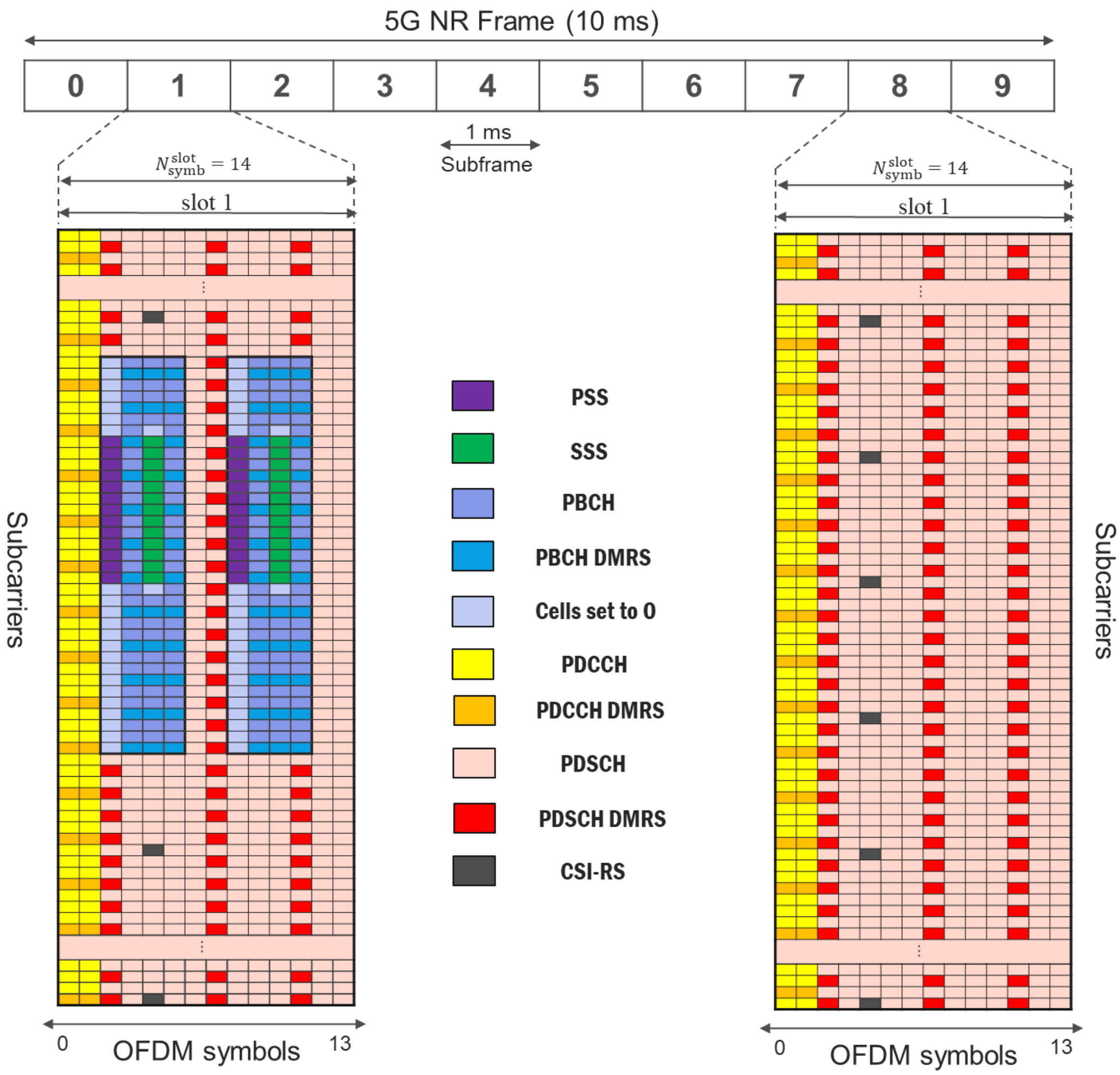

Figure 16. Frame structure for SFI = 0 (10 subframes, 100% Downlink).

- **Physical Broadcast Channel (PBCH):** Downlink channel used to transmit the static part of the System Information (SI), which is conveyed at the Master Information Block (MIB). 5G NR MIB is similar to the LTE MIB, since both are defined as a set of bits transmitted to all the UEs to perform the initial access of the cell. PBCH content also includes DMRS signals, which are used during the beam management process. All the PBCH content is QPSK modulated.

- **Primary and Secondary Synchronization Signals (PSS, SSS):** Physical signals used to enable UE synchronization. PSS and SSS provide radio frame timing information and the Cell ID to all UEs for the initial cell search. In addition, they are also used for the beam management in IDLE state. PSS, SSS, PBCH, PBCH-DMRS and cells set to 0 are transmitted together in SS/PBCH blocks. Each SS/PBCH block consists of 240 subcarriers and 4 OFDM symbols, i.e. 960 REs in total. The allocation of SS/PBCH blocks in frequency domain is specified by the high-layer parameter *ssb-subcarrierOffset*.

Regarding time domain, SS/PBCH blocks are transmitted in periodical burst sets, where the number of blocks and its allocation depends on the numerology and the frequency band. An example of SS/PBCH block allocation within a slot is given in Figure 17.

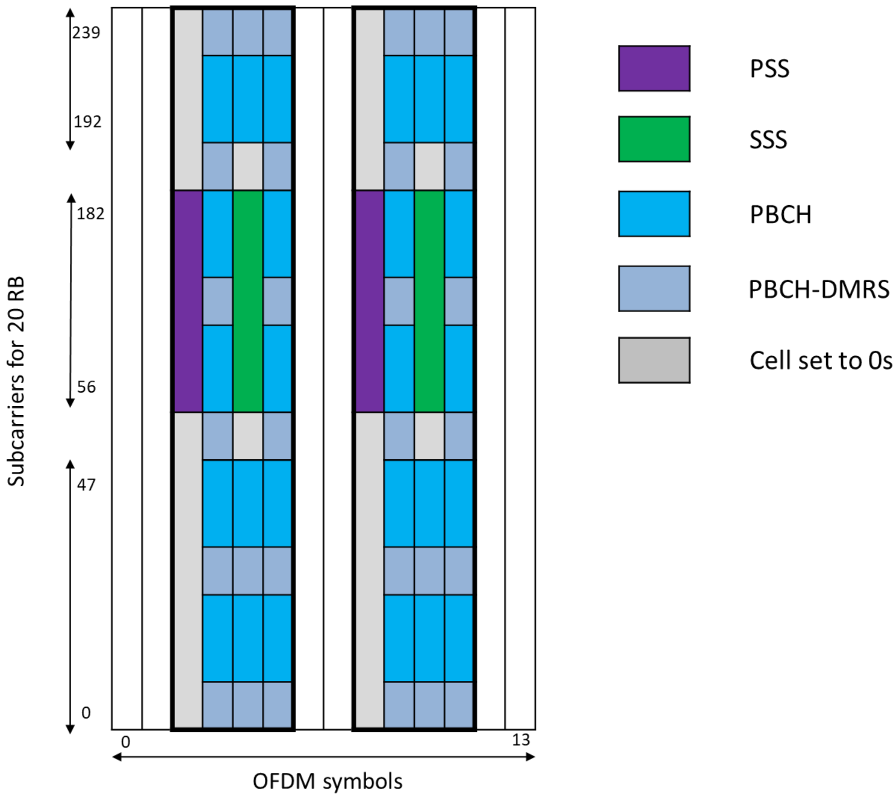

Figure 17. SS/PBCH Blocks in one slot.

- **Physical Downlink Control Channel (PDCCH):** Physical channel used to specify the scheduling and resource allocation of the data content to all the UEs that request it. It can also be used to configure HARQ (Hybrid Automatic Repeat Request) retransmissions, link adaptation or uplink transmissions. PDCCH useful information is transmitted at the DCI. 5G NR defines different DCI formats depending on the functionality and the scheduled physical channel. DCI payload is polar encoded, QPSK modulated and mapped in one or more control-channel elements (CCE). The number of CCEs depends on the Aggregation Level (AL), which has five possible values {1,2,4,8,16}. Each CCE is composed of 6 REGs, where a REG is defined as one RB allocated in one OFDM symbol. The total number of CCEs and REGs associated to each UE are mapped within PDCCH in CORESETs packets. CORESET structure is shown in Figure 18.

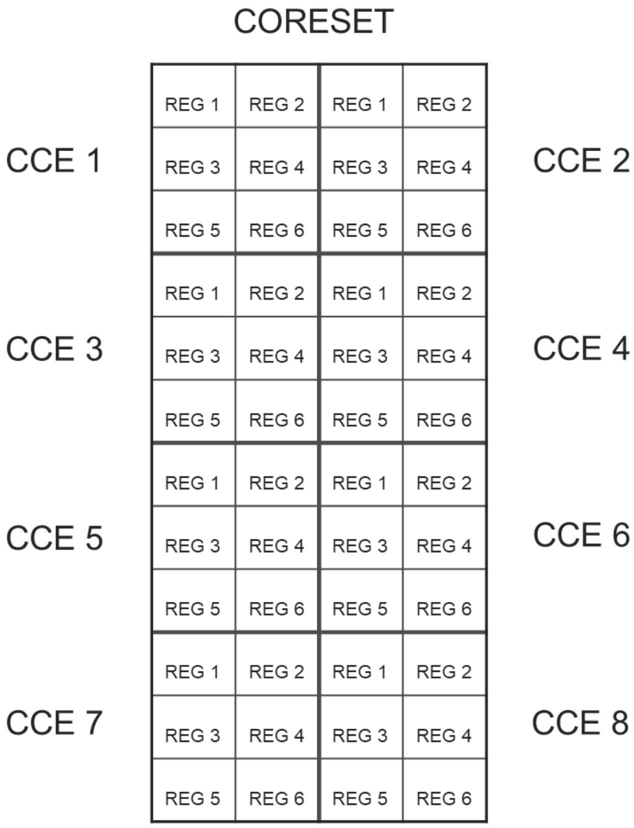

Figure 18. CORESET structure.

In frequency domain, CORESETs are allocated in the frame structure depending on high-layer parameters. Regarding time domain allocation, CORESETs can be transmitted at OFDM symbols 0,1 or 2 of subframes that do not convey SS/PBCH blocks in that regions. CORESET also includes DMRS signals to allow the correct demodulation of the PDCCH. Figure 19 illustrates CORESET structure allocation with AL = 1.

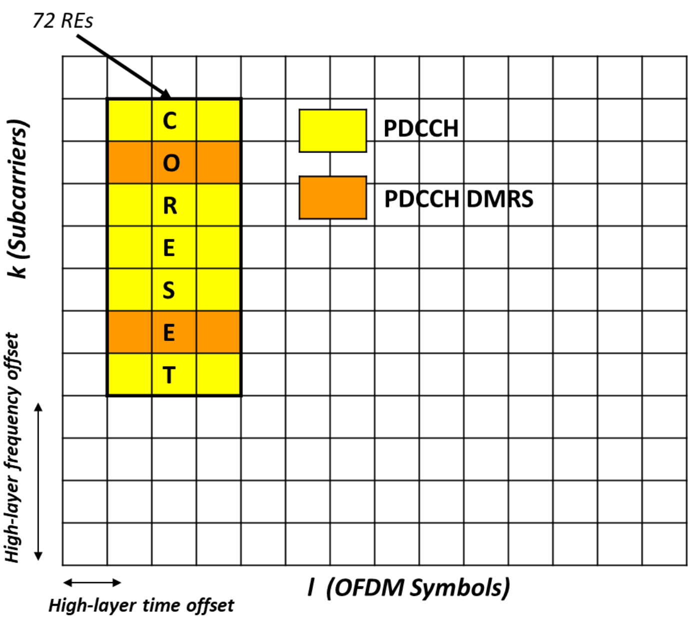

Figure 19. CORESET allocation in 5G NR slot.

- **Physical Downlink Shared Channel (PDSCH):** Physical channel used to transmit all the data content and the System Information Blocks (SIB). PDSCH content is distributed in all REs where the SS/PBCH and PDCCH are not allocated. The number of RBs associated to PDSCH transmissions depends on the available bandwidth and numerology. PDSCH information is LDPC encoded and it can be modulated with QPSK, 16QAM, 64QAM or 256QAM. PDSCH includes different types of RS such as DMRS, CSI-RS and PT-RS.

- **Reference Signals:** 5G NR defines different types of reference signals depending on its functionality:

    - **Demodulation Reference Signals (DMRS):** Reference signals used to enable the channel estimation for PBCH, PDCCH and PDSCH. DMRS time and frequency allocation depends on the selected DMRS pattern. Each pattern is described by different parameters such as the DMRS configuration type, DMRS mapping type and the DMRS position. DMRS patterns are shown in Figure 20.

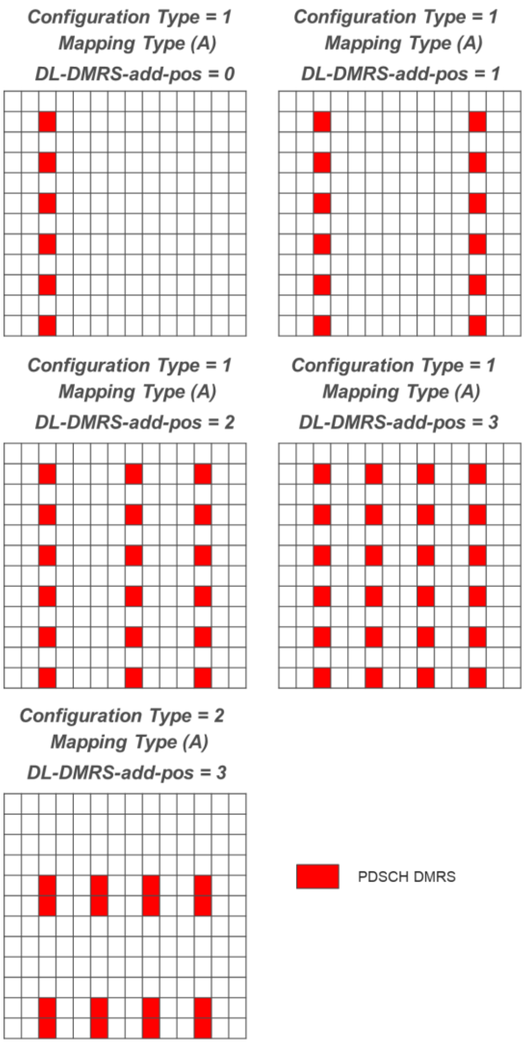

Figure 20. 5G NR DMRS Patterns.

- **Channel State Information Reference Signals (CSI-RS):** Reference signals used to provide channel state information (CSI) to the UE. CSI-RS are also used for beam management in CONNECTED state and for tracking and interference measurement. As a consequence, different types of CSI-RS are defined: Non-Zero-Power CSI-RS (NZP CSI-RS), CSI Interference Management (CSI IM) and CSI-RS for frequency and time tracking (TRS).

- **Phase Tracking Reference Signals (PT-RS):** Reference signals used to estimate and correct the phase noise in the PDSCH. PT-RS are only used at high frequency ranges (FR2).

An example of PDCCH, PDSCH and RS allocation in a slot is shown in Figure 21.

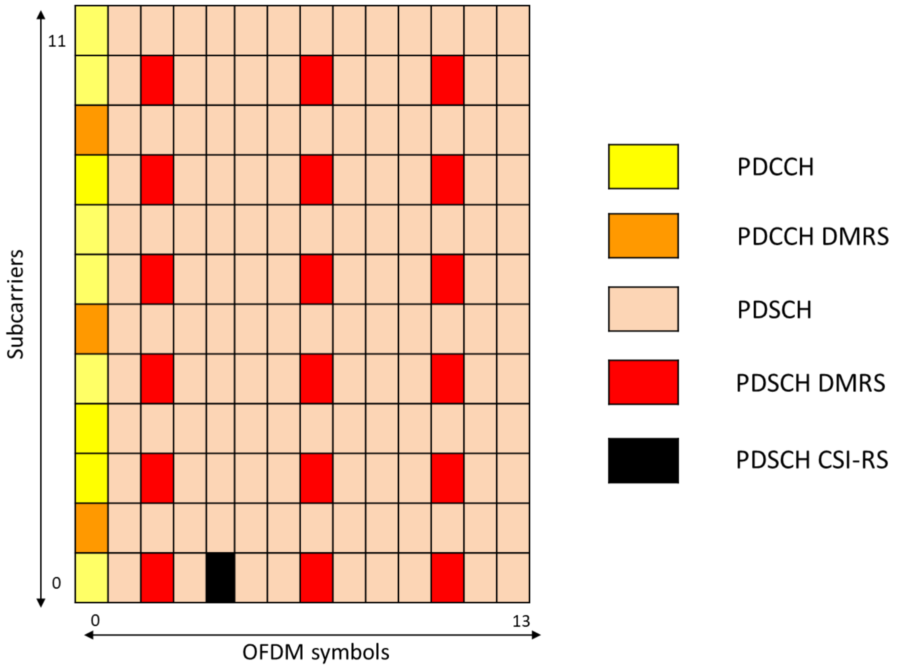

Figure 21. PDCCH, PDSCH and RS allocation in a 5G NR slot.

5.2 5G NR Terrestrial Broadcast

According to the analysis performed in Chapter 4, this section analyses the design of a potential 5G Terrestrial Broadcast solution. The proposed design introduces new PTM capabilities into the existing 5G unicast solution in order to deliver traditional media content (e.g. TV services) over the existing mobile network for LPLT and HPHT scenarios. 5G Terrestrial Broadcast looks to provide a solution able to deliver high quality content for mobile and fixed TV reception with the same quality and robustness than the traditional broadcast systems. Thanks to it, traditional TV services will be delivered over dedicated transmissions to every user without the need for UEs to register/attach to the network.

To develop this solution, different architecture, service and physical layer enhancements need to be introduced over the 5G unicast design, which has been considered as reference. Since this study is only focused on the physical layer design, the architecture and service enhancements have not been analysed.

The physical layer solution has been designed to fulfil the list of 3GPP requirements described previously. To reach these requirements, physical layer has to enable different multicast/broadcast capabilities such as the provision of large area coverage (up to national wide area), high spectral efficiency with reduced overheads and the possibility to cover different mobility scenarios, i.e. from fixed rooftop to high mobility reception.

To fulfil all these requirements, this subsection proposes the design of a SFN operation mode as a basis of the new 5G Terrestrial Broadcast air interface. The new air interface design has considered the existing 5G unicast design as a reference. Thus, the existing air interface components, i.e. coding, framing, scheduling and physical channels have been reused as much as possible. However, in order to introduce specific SFN capabilities, some modifications related to the CP lengths, RS patterns and the control region have been identified and analysed.

All the required modifications have been introduced under the principle of preservation in order to create an air interface design compatible with 5G unicast solution.

5.2.1 Cyclic prefix

5G Terrestrial Broadcast reuses the unicast physical channel solution, i.e. PDSCH, to convey data transmissions to all UEs interested in traditional media services. The reuse of this channel allows to provide backwards compatibility with the current 5G unicast solution. However, it also implies some limitations for the design of a SFN operation mode.

PDSCH is designed over the 5G unicast frame structure, which depends on a scalable numerology solution. As explained previously, 5G unicast numerology is defined by μ, a positive integer factor which has an influence on the subcarrier spacing, OFDM symbol length and cyclic prefix length. The number and the duration of the slots in the subframes are also affected by μ, since 5G unicast framing defines fixed duration for subframes, i.e. 1 ms, and a fixed number of OFDM symbols. The relation between these parameters was shown in Table 10.

From the SFN scope, the CP length dependence on numerology supposes a limitation for the maximum ISD between transmitters. As shown in Table 11, the current 5G unicast solution enables a maximum CP length of 4.7 µs, which is obtained for numerology μ =0. According to this value and the procedure described in Equation 1, the maximum ISD in SFN environments allowed by the 5G unicast solution is equal to 1.4 km. Since the 3GPP requirement looks to enable SFN transmissions with cell radius up to 100 km, the current 5G numerology is clearly not valid for the creation of an SFN mode in 5G Terrestrial Broadcast.

μ	SCS (kHz)	Type CP	Tcp (μs)	ISD (km)
0	15	Normal	4.69	1.41
1	30	Normal	2.34	0.7
2	60	Normal	1.17	0.35
		Extended	4.16	1.25
3	120	Normal	0.59	0.18
4	240	Normal	0.29	0.09

Table 11. CP for 5G positive numerologies.

As a solution, this master thesis proposes the definition of additional CP values to reach larger ISDs. Based on this, two different sets of CP values have been proposed for the delivery of SFN transmissions through LPLT and HPHT deployments. On the one hand, LPLT deployments have been considered as a good solution to enable SFN transmissions in small scale scenarios where the ISDs can reach values up to 20 km, e.g. urban areas. On the other hand, HPHT scenarios have been considered for transmissions in large scale scenarios with ISDs larger than 20 km, e.g. national or regional coverage.

This classification has been made according the definition provided by several studies such as [11] or [16].

5.2.1.1 CP values for LPLT deployments

In order to define new CP values for LPLT deployments this study proposes the design of a scalable 5G numerology solution with negative μ values combined with the use of the Extended CP. The creation of negative μ values implies the definition of narrower subcarrier spacings, longer OFDM symbol lengths and therefore longer cyclic prefix lengths, which are equivalent to larger ISD distances in SFN environments. The proposed numerology combinations are shown in Table 12.

μ	SCS (kHz)	Tu (μs)	Extended CP (μs)	ISD (km)
0	15	66,66	16,66	5
-1	7.5	133,33	33,33	10
-2	3,75	266,66	66,66	20

Table 12. Extended CP for 5G negative numerologies

As it can be observed, three numerology and Extended CP combinations have been defined. Thanks to this, 5G Terrestrial Broadcast offers a set of ISDs from 5 km up to 20 km that allow to deploy SFNs in small, medium and large cells for LPLT environments.

Nevertheless, the design of negative numerology finds a framing limitation due to the μ factor influence. Since 5G framing defines a fixed duration for subframes and a fixed number of OFDM symbols in a slot, changes in μ imply some variations on the number and the duration of slots in subframes. Consequently, when μ reaches negative values, the OFDM symbol and slot duration gets increased and slots span over more than one subframe in time domain. This impact is shown in Table 13.

μ	OFDM Symbols/slot	Slot (ms)	Slots/subframe
0	14	1	1
-1	14	2	1 slot spans 2 subfr.
-2	14	4	1 slot spans 4 subfr.

Table 13. Number of slots per subframe with the proposed negative numerologies.

To solve this limitation, some small changes need to be introduced over the framing structure in order to provide a flexible and scalable solution compatible with negative integer numerologies.

In [17], the introduction of a 5G frame structure based on the use of mini-slots was proposed to enable SFN negative numerologies where slots span over different subframes or even frames. Mini-slots are a small framing unit formed by a group of OFDM symbols (2, 4 or 7) and used in high numerologies to provide a more granular scheduling for broadcasting packet transmissions. Based on this concept, this master thesis proposes the use of mini-slots for negative numerologies. As a consequence, when several OFDM symbols are grouped in one mini-slot, the OFDM symbol expansion is mapped into the new framing unit and the slot is able to keep the original length. In particular, the use of mini-slots is proposed for numerologies μ = -1 and μ = -2 combined with Extended CP.

When μ = -1 numerology is selected, six mini-slots compose the subframe, grouping each mini-slot two CP OFDM symbols. Regarding μ = -2 numerology, each mini-slot can convey up to 4 OFDM symbols and therefore 3 mini-slots compose the subframe. An example of both frame structures is shown in Figure 22.

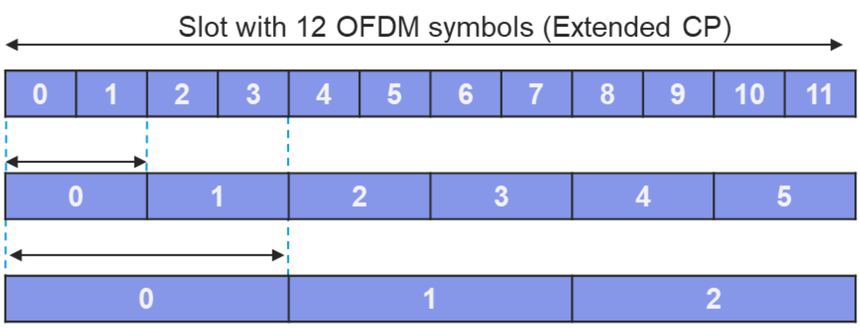

Figure 22. Slot decompositions in mini-slots of 2 or 4 OFDM symbols.

It should be noted that if lower negative numerologies were considered, e.g. μ = -3 or μ = -4, larger ISDs could be covered. However, for narrower subcarrier spacings a non-integer number of mini-slots would be required and therefore more framing incompatibilities would be introduced. An example of this framing limitation is shown in Figure 23.

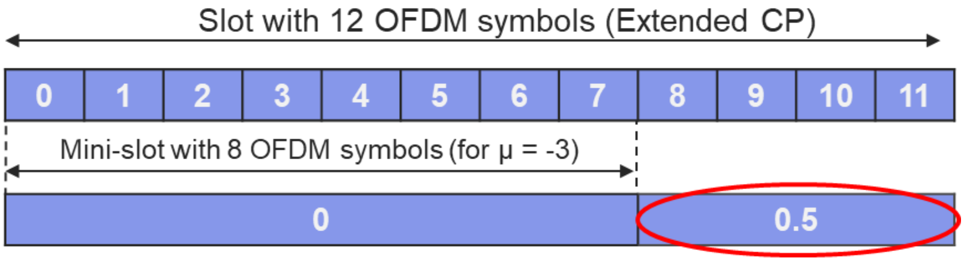

Figure 23. Framing limitation for mini-slot configuration.

5.2.1.2 CP values for HPHT deployments

Apart from LPLT deployments, this master thesis also proposes the definition of three different CP values suitable for HPHT deployments: 100 μs, 200 μs and 333.33 μs. The proposed set of CPs is not related to the numerology concept and can be considered as an additional feature introduced to enable large coverage areas in 5G Terrestrial Broadcast SFN operation. For this set of CPs, the required SCS, useful OFDM symbol duration and ISD are the following:

SCS (kHz)	Tu (μs)	TCP (μs)	OFDM Symbols/subframe	ISD (km)
2.5	400	100	2	30
1.25	800	200	1	60
1.5	666.66	333.33	1	100

Table 14. Additional CPs for 5G Terrestrial Broadcast in HPHT scenarios

As shown in Table 14, the introduction of this set of CPs allows to cover ISDs up to 100 km through HPHT deployments in a SFN mode. It should be highlighted that the obtained SCSs and the corresponding number of OFDM symbols allocated in a subframe are not based on the scalable 5G unicast numerology definition. This fact implies the unfulfilment of the 5G unicast frame structure, where 14 OFDM symbols are allocated in each slot. As a consequence, it can be assured that for introducing large CPs for HPHT scenarios, some framing limitations have to be omitted.

Thanks to the definition of these two sets of CPs for LPLT and HPHT, 5G Terrestrial Broadcast is able to cover a large set of area sizes in SFN scenarios. However, the definition of larger CPs also introduces some limitations and restrictions:

- The introduction of larger CPs introduces larger overheads due to the insertion of redundant information. A detailed calculation of the overhead introduced by the new CP values is provided in Chapter 6.

- The definition of large CPs implies the configuration of narrower subcarrier spacing. As a consequence, a noticeable vulnerability to high-speed scenarios due to Doppler effect is introduced.
- The definition of narrower subcarrier spacings implies the creation of longer OFDM symbols, large FFT sizes are required and consequently the complexity of the system gets increased. An example of FFT size increase for LPLT scenarios is shown in Table 15.

μ	SCS (kHz)	Tu (µs)	TCP (µs)	FFT Size (samples)
0	15	66,66	16,66	1024
-1	7.5	133,33	33,33	2048
-2	3,75	266,66	66,66	4096

Table 15. Associated FFT size for the proposed negative numerologies (BW = 10 MHz).

5.2.2 Reference Signals

Reference signal patterns are traditionally defined by the time and frequency separation between reference signals, which is given by the D_x and D_y parameters. The correct selection of these parameters is fundamental for enabling a correct channel estimation process.

As mentioned in previous subsections, D_x, specifies the separation of pilot bearing carriers along different OFDM symbols in frequency domain. In an SFN, where echoes generate severe fading, the selection of a proper D_x is critical and has a direct influence in the value of the Nyquist limit, defined as T_p. When both frequency and time interpolation are implemented, the Nyquist limit gets the value:

$$T_p = \frac{T_u}{D_x} \tag{6}$$

As it can be seen on Equation 6, T_p is increased when the useful symbol duration becomes larger (i.e. for narrower SCS) and in general for dense SP patterns since a more accurate channel estimation can be performed in the frequency domain.

Regarding D_y, it specifies the separation of pilot bearing carriers for the same subcarrier in time domain. As shown in Equation 3, D_y makes an impact on the theoretical Doppler limit and therefore on the mobility conditions allowed in a SFN scenario.

Ideally, low D_x and D_y values can be seen as the perfect combination to enable large Nyquist limits and high speeds conditions. However, this assumption would imply the design of a high-density pilot pattern and therefore a large overhead value related to the reference signals design. As for the CP, a detailed overhead analysis for the RS patterns will be provided in the following subsection.

Based on this analysis and considering the fading conditions introduced at the SFN environments, the reuse of the 5G unicast RS patterns may not be sufficiently accurate. As a consequence, specific SFN RS patterns are designed. To introduce new RS patterns, the ones specified in LTE eMBMS and 5G unicast have been considered as a reference. Table 16 and Table 17 show the different reference signal patterns and the corresponding D_x and D_y values defined in LTE eMBMS and 5G unicast:

SCS (kHz)	D_x	D_y
15	1	8
7.5	2	4
1.25	3	2

Table 16. LTE eMBMS Rel.14 RS Patterns

As it can be seen in Table 16, LTE eMBMS defines different D_x and D_y values for each SCS configuration. When large SCS are selected, lower D_x values are defined in order to provide a better estimation on the frequency domain. Since large SCS implies better Doppler tolerance, higher D_y values are configured. In contrast, when narrow SCSs are configured the density in frequency domain is decreased, i.e. higher D_x values, and the density in time domain gets increased, i.e. lower D_y values, in order to provide higher robustness against Doppler effect.

Regarding 5G unicast, two different configurations are shown in Table 17. Both configurations are valid for all the SCS values. Regarding the density on frequency domain, D_x remains constant with a value equal to 2. Regarding D_y, depending on the mobility conditions, the use of D_y value 3 or 9 can be more or less suitable.

5G Unicast Configuration	D_x	D_y
Config. 1	2	9
Config. 2	2	3

Table 17. 5G Unicast RS Patterns

Considering these patterns as a reference and according to guidelines provided for the D_x and D_y values, Table 18 shows the SFN reference signal patterns defined for the new 5G Terrestrial Broadcast solution.

SCS (kHz)	OFDM symbols/slot	Tu (µs)	CP (µs)	D_x	D_y
15	12	66,66	Extended (16.66)	2	3
7.5	6 (Minislots)	133,33	Extended (33.33)	2	3
3.75	3 (Minislots)	266,66	Extended (66.66)	2	2
2.5	2	400	100	2	2

1.5	1	666.66	333.33	2	2
1.25	1	800	200	3	2

Table 18. 5G Terrestrial Broadcast RS patterns

As it can be seen, SFN reference signal patterns are mainly based on the 5G unicast RS design. For SCS 15 kHz and 7.5 kHz, the same RS pattern than unicast is defined. When narrower subcarrier spacings are considered, i.e. 3.75 kHz, 2.5 kHz, 1.5 kHz and 1.25 kHz, more vulnerability against Doppler effect is obtained and therefore denser patterns are defined (lower D_y values). At the same time, narrow SCS also imply more density on the frequency domain and therefore higher D_x values can be selected. The introduction of high density patterns enables better channel estimation performance at the expense of introducing more overheads. Based on these values, the configurations defined in Table 18 has been represented in Figure 24:

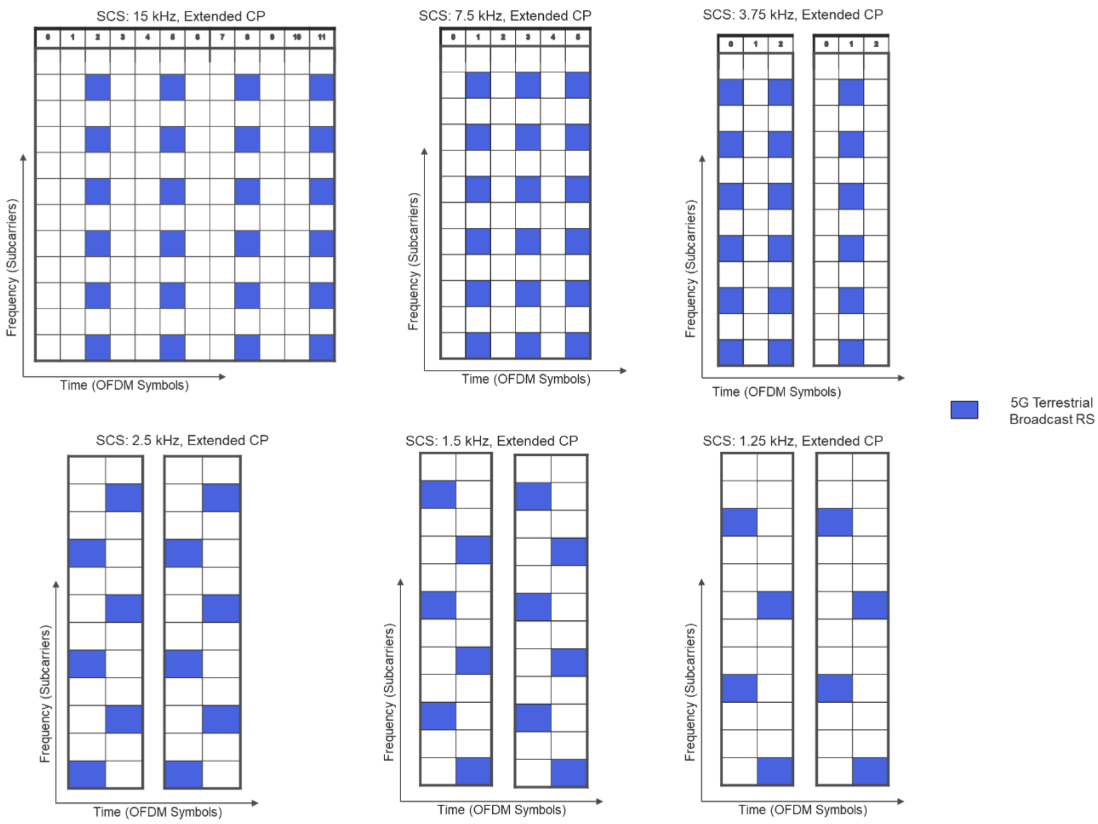

Figure 24. 5G Terrestrial Broadcast RS patterns.

5.2.3 Control region

As explained in Chapter 3, if 100% multicast/broadcast resource allocation is performed over the SFN operation mode, a common and specific multicast/broadcast control region has to be defined. 5G Multicast/broadcast control region is needed to convey all the acquisition, synchronization and signalling information, i.e. PBCH, PSS, SSS, PDCCH and PDSCH SIBs information, required to enable the access to the multicast/broadcast data content.

As explained previously, LTE enTV was one of the first multicast/broadcast solutions to include the transmission of a periodic control region, i.e. CAS. enTV CAS is transmitted every 40 ms with a unicast-based numerology that may limit the coverage for the SFN operation mode. In order to design a new control region for 5G Terrestrial Broadcast, the use of the CAS for LTE enTV has been considered as a reference.

The new control region solution, which has been envisaged as 5G CAS, has been defined with a similar parameter configuration. On the one hand, since 5G and LTE eMBMS keep the same frame duration, 5G CAS is also transmitted every 40 ms over the subframe #0. Regarding the numerology option, 5G CAS includes some innovation. Apart from the use of the traditional numerologies, i.e. 15 kHz, negative numerologies 7.5 kHz and 3.75 kHz are also considered to deliver control region content for the new 5G Terrestrial Broadcast solution. Thanks to it, negative numerologies enable to cover large ISDs and therefore to optimize the transmission of the 5G CAS in SFN scenarios.

5.3 3GPP Requirement Evaluation

Once the 5G Terrestrial Broadcast physical layer has been designed, it is necessary to evaluate if it the solution is able to fulfil all the 3GPP requirements related to the design of a new PTM solution. To that end, following the same methodology than for Chapter 4, this section evaluates the performance of the system for each 3GPP requirement through inspection and analysis methodologies.

R1: PTM solution shall allow to deliver the existing multicast/broadcast services (e.g. TV, streaming, group communications, etc.) and new services (e.g. IoT, V2X, etc).

5G Terrestrial Broadcast solution is designed to deliver traditional TV services over the existing mobile network following a 3GPP backwards compatibility philosophy. In particular, 5G Terrestrial Broadcast has been designed considering 5G unicast and LTE eMBMS as a basis. According to this, R1 is fulfilled.

R2: PTM solution shall allow to adjust dynamically the multicast/broadcast service area depending on the service requirements, user distribution, etc.

5G Terrestrial Broadcast introduces a large CP granularity in the new SFN operation mode. The use of negative numerologies together with the definition of large and fixed CPs enable to cover ISDs from local to national coverages. Based on this and assuming the proper design of the architecture and service layers, the new 5G Terrestrial Broadcast solution is able to adjust the multicast/broadcast service area depending on different system requirements. This aspect is fully invisible to the UE, which is not involved in feedback or uplink transmissions to request the area adjustment.

R5: PTM solution shall allow static and dynamic resource allocation between unicast and multicast/broadcast services, where multicast/broadcast resources shall be allocated from 0% up to the 100% (downlink-only mode with one or more MBMS dedicated carrier).

The new air interface solution includes the design of a specific multicast/broadcast control region, based on the use of LTE enTV CAS. 5G CAS is transmitted periodically to convey control and synchronization information to the different UEs. Thanks to it, 5G Terrestrial Broadcast allows the static allocation of multicast/broadcast services on nearly the 100% of the physical resources for the SFN operation mode.

R7: PTM solution shall include a SFN operation mode to cover large geographical areas up the size of a country and also cells with up to 100 km of radius shall be created. Local, regional and national broadcast areas shall also be possible.

5G Terrestrial Broadcast solution introduces the use of a scalable and high-performing SFN operation mode. In it, apart from the corresponding service and architecture layer features, different physical layer enhancements are included over the 5G unicast air interface in order to enable local, regional and national coverage. The use of longer CPs, new RS patterns and a new control region are the main novelties introduced.

Regarding the CP, two sets are introduced to enable larger ISDs for LPLT and HPHT deployments. LPLT CPs are introduced by means of the use of negative numerologies over the existing PDSCH structure. In this solution, narrow SCS like 15 kHz, 7.5 kHz and 3.75 kHz are combined with the Extended CP to reach ISDs from 5 up to 20 km. To enable that, the use of mini-slots is introduced over the existing 5G unicast frame structure. With respect to HPHT, large scale SFN transmissions are enabled by defining longer CP values over the existing physical channel structure, i.e. PDSCH. 5G Terrestrial Broadcast defines three different CPs associated to the corresponding SCS: 100 µs for 2.5 kHz, 200 µs for 1.25 kHz and 333.33 µs for 1.5 kHz. These values imply the coverage of ISDs from 30km up to 100 km.

With respect to the new RS design, 5G Terrestrial Broadcast includes specific SFN patterns to enable a correct channel estimation in large scale scenarios. Different patterns are defined for each SCS configuration, enabling two possible values for D_x and D_y: $D_x = 2$ or 3 and $D_y = 2$ or 3. The variation of both parameters gives an accurate channel estimation depending on the SCS configuration and the mobility conditions at the expense of introducing some overheads.

Finally, to enable a larger coverage, negative numerologies are used in the 5G CAS design to reduce the coverage limitation introduced by the control region. In principle, new 5G CAS solution allows ISD up to 20 km with negative numerologies. Thanks to it, 5G CAS allows to reach four times the coverage of the LTE enTV CAS solution for the control content. Additional coverage simulations should be performed in order to determine the real limitation introduced.

Based on this description, it can be concluded that 5G Terrestrial Broadcast is able to enable SFN operation with ISDs up to 100 km and therefore, this requirement is met.

R8: PTM solution shall be able to deliver content to UE with high spectral efficiency in fixed, portable and mobile conditions. Speeds up to 250 km/h shall be supported.

5G Terrestrial Broadcast supports different mobility conditions thanks to the use of different subcarrier spacings and RS patterns. As shown in Equation 3, the definition of narrow SCS and low density RS patterns may limit the maximum Doppler tolerance and therefore the mobility allowed by the system. According to this, Table 19 shows the maximum mobility conditions allowed by the system.

SCS (kHz)	Tu (µs)	CP (µs)	D_y	Maximum Fd (Hz)	Maximum Speed for 700 MHz (Km/h)	Maximum Speed for 4 GHz (Km/h)
15	66,66	16.66	3	2000.32	3086.2	540.08
7.5	133,33	33.33	3	1000.04	1542.9	270.01
3.75	266,66	66.66	2	751.51	1159.48	202.90
2.5	400	100	2	500	771.42	135
1.5	666.66	333.33	2	250	385.71	67.5
1.25	800	200	2	250	385.71	67.5

Table 19. Maximum speed limits for 5G Terrestrial Broadcast

As it can be seen, the 250 km/h requirement is met depending on the SCS configuration and the frequency of operation. For the 700 MHz band, all the SCS configurations are able to reach the mobility requirement. However, for 4 GHz, only SCS 15 kHz and 7.5 kHz are able to enable the highest system performance for speeds higher than 250 km/h. This limitation introduced is due to the use of new SFN numerologies, which provide longer CP at the expense of enabling lower mobility conditions. According to Equation 3, the use of longer OFDM symbols and the introduction a higher frequency of operation (4 GHz) limit the mobility performance. According to this, SCS 1.25 kHz and 1.5 kHz provide the lowest mobility tolerance: 67.5 km/h for 4 GHz. To face these limitations, the different RS patterns have been optimized with the lowest possible D_y values: 2 and 3. The use of denser RS patterns means the introduction larger RS overheads.

Based on this, it can be assured that the new 5G Terrestrial Broadcast solution is able to fulfil the mobility requirement for the right SCS, RS pattern and frequency of operation combinations.

R9: PTM solution shall enable the use of different types of hardware and software, e.g. MIMO, to improve multicast/broadcast capacity and reliability.

5G Terrestrial Broadcast enables the use of MIMO mechanisms by reusing the 5G unicast physical channel structure. 5G Terrestrial Broadcast inherits the use of PDSCH, which enables the transmission and reception of up to 8 layers. Thanks to the use of MIMO spatial multiplexing techniques, the new terrestrial broadcast solution is able to improve the capacity and reliability of the system by an 8 factor.

Conclusions

Based on this analysis, Table 20 summarizes the fulfilment of all the 3GPP requirements and provides a fair comparison between the evaluated 5G Terrestrial Broadcast and LTE enTV and ATSC 3.0:

Requirements	5G Terrestrial Broadcast	LTE enTV	ATSC 3.0
Traditional TV services over the existing cellular network	Enabled	Enabled	Not enabled: Specific DTT solution, not 3GPP compatible, not efficient.
Adjust coverage dynamically	Enabled: 7 possible area sizes	Enabled: 4 possible area sizes	Enabled: 12 possible area sizes.
100% multicast/broadcast allocation	Enabled: 5G CAS	Enabled: LTE enTV CAS	Enabled: Broadcast solution with bootstrap
SFN mode with ISD up to 100 km	Enabled: ISD up to 100 km	Not enabled: ISD up to 60 km	Enabled: ISD up to 211 km.
Mobility conditions up to 250 km/h	Enabled for wide SCS, dense RS patterns and 700 MHz	Enabled for wide SCS and dense RS patterns	Enabled for few transmission modes.
MIMO capabilities	Enabled: PDSCH and MIMO 8 layers	Not enabled: PMCH	Enabled: MIMO 2 layers

Table 20. Requirement fulfilment for 5G Terrestrial Broadcast, LTE enTV and ATSC 3.0

As shown in Table 20, 5G Terrestrial Broadcast is able to meet all the 3GPP requirements. If its performance is compared with the rest of terrestrial broadcast technologies, different conclusions can be drawn.

- Regarding the delivery of traditional TV services over the existing cellular architecture, 5G Terrestrial Broadcast and LTE enTV are suitable options while ATSC 3.0 does not fulfil the requirement due to the lack of compatibility with the existing cellular standards.
- With respect to the dynamic adjustment of the coverage, the three solutions are able to meet the requirement, offering ATSC 3.0 the largest granularity and LTE enTV the lowest.

- If the 100% multicast/broadcast allocation is considered, the three technologies are also able to meet the requirement. In particular, 5G Terrestrial Broadcast and LTE enTV enable a nearly 100% allocation due to the use of CAS while ATSC 3.0 conveys control information in the bootstrap.
- Regarding the design of a SFN operation mode covering ISDs up to 100 km, 5G Terrestrial Broadcast and ATSC 3.0 are the only solutions able to meet this requirement by means of the introduction of large CPs.
- With respect to mobility, 5G Terrestrial Broadcast supports higher mobility conditions than LTE enTV and ATSC 3.0. Even so, all the 5G configurations are not able to meet the 250 km/h requirement.
- Finally, 5G Terrestrial Broadcast and ATSC 3.0 are the only solutions able to fulfil the MIMO capabilities requirement thanks to the use of compatible physical layer designs.

Chapter 6. 5G Terrestrial Broadcast Evaluation in SFN Environments

This section evaluates the 5G Terrestrial Broadcast air interface performance in different SFN scenarios. The evaluation has been carried out through the analysis of different physical layer parameters. The obtained results have also been compared with ATSC 3.0 and LTE enTV in order to evaluate the impact of the new terrestrial broadcast solution.

To perform this evaluation, different KPIs related to the SFN operation mode have been defined. The methodology used to evaluate these KPIs was described in Chapter 2 and it is structured around three different methods: inspection, analytical and link-level simulations. The list of evaluated KPIs and the corresponding methodology used for the analysis is shown in Table 21.

KPI/ Methodology	Inspection	Analysis	Link-level Simulations
Overheads	X	X	
BICM spectral efficiency			X
Spectral efficiency		X	
Data rate		X	

Table 21. KPI evaluation and methodology

According to this classification, first subsection provides a description of the SFN environment where the most influent factors and its impact on the physical layer parameters has been analysed. After that, the set of KPIs has been described and evaluated according to the described methodologies. Finally, some conclusions related to the performance of the different technologies have been drawn.

6.1 SFN Environments

6.1.1 Channel model

As explained in Chapter 3, the received SFN signal consists of a set of echoes arriving with different powers and delays depending on the channel and the distance to the SFN transmitter.

In this study, SFN environment has been modelled as a network composed of two SFN transmitters delivering the same content with the same amplitude and power. Different ISDs and therefore different echo delays have been analysed in order to evaluate its influence on the system performance.

To perform link-level simulations, SFN scenarios have been modelled through a channel model named: ‘Simple two path profile, 0 dB echo’. 0 dB echo channel is defined at the DVB-T2 Implementation Guidelines [18] as a channel model composed of two paths with the same amplitude and a time delay equivalent to 90% of the CP duration. In this study, the channel has been modified and extended to enable different delays.

Equation 7 describes the 0 dB Echo channel model response h(t), where δ is the delta function, τ is the echo delay and λ is the relative amplitude in a linear scale:

$$\boldsymbol{h(t) = \delta(t) + \lambda \cdot \delta(t - \tau), \quad 0 \leq \lambda \leq 1, \tau \geq 0} \tag{7}$$

The impact of the echo delay is one of the most influent factors in the 0 dB Echo channel response. As shown in Figure 25, higher delays cause several frequency fadings on the channel, creating a more unfriendly scenario.

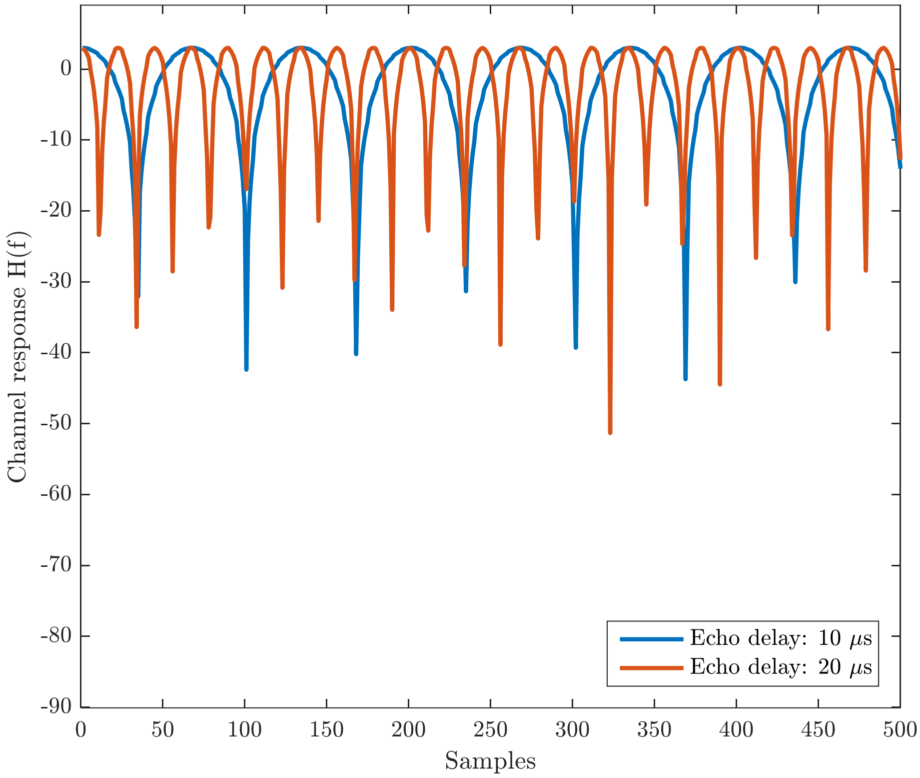

Figure 25. 0 dB Echo channel response.

0 dB Echo includes a frequency shift defined for the second path. In order to simplify the simulation process, this frequency shift has not been considered. As a consequence, both contributions have been added in-phase, providing a more critical scenario.

6.1.2 Quality of Service and CNR

The set of link-level simulations included in this study has been obtained following the simulation chain described in Annex A. Based on this, physical layer simulator is able to provide different Quality of Service (QoS) measurements, in our case expressed as BLER, for the minimum CNR required by the system. In particular, BLER< 0.1% requirement has been set up. According to this requirement, the simulator will find the CNR required to receive less than 1 out of 1000 transmitted subframes erroneously. To obtain these QoS measurements, only CNR values up to 30 dBs have been considered as realistic signal to noise conditions.

6.1.3 Channel Estimation

Link-level simulations conducted in SFN scenarios are affected by different fading and multipath effects which need to be properly estimated. To estimate the channel, a two dimensional process performed across time and frequency domains is usually employed. This procedure is mainly based in two steps:

1. First, the channel is estimated at the RS positions. A simple way of estimation is the Least Square (LS) method which is performed through two one dimensional processes, one for each dimension [19]. Through this method, the received signal ($Y_i[m]$) and the estimated channel ($\widehat{H}_i[m]$) can be modelled for SFN scenarios as shown in Equations 8 and 9.

$$Y_i[m] = H_i[m]X_i[m] + \delta_{i_{ISI}}[m] + \delta_{i_{ICI}}[m] + N_i[m] \quad (8)$$

$$\widehat{H}_i[m] = \frac{Y_i[m]}{X_i[m]} = H_i[m] + \frac{\delta_{i_{ISI}}[m] + \delta_{i_{ICI}}[m] + N_i[m]}{X_i[m]} \quad (9)$$

   where $X_i[m]$ is the transmitted signal, $H_i[m]$ is the channel response, $N_i[m]$ is the AWGN noise and $\delta_{i_{ISI}}[m]$ and $\delta_{i_{ICI}}[m]$ [m] express additional degradation due to ISI and ICI when the echoes are received outside the CP. The process is carried out per OFDM symbol (i) and subcarrier [m].

2. The second step is based on the extension of the channel estimation process to the rest of subcarriers and OFDM symbols in the frame. This process is generally carried out by a two dimensional filtering based on interpolation. The selected interpolation method is one of the most critical steps in the channel estimation procedure. In particular, in SFN channels a very accurate interpolation method is required in frequency domain due to the presence of frequency selective fading. Over the years, the existing literature has analysed different channel estimation methods based on linear, noise estimation and FFT-based estimation techniques:

   - **Linear interpolation**: Is a straightforward method based on the estimation of different subcarriers by the result of a linear interpolation between the LS estimates. It can be used over both time and frequency domain. Linear interpolation is one of the most common interpolation techniques since it provides good performance combined with low computational complexity. As main disadvantage, the method lacks of accuracy when severe fading conditions are given.

- **DFT-based interpolation:** Method based on the estimation of different subcarriers through the application of an IDFT and DFT process [20]. DFT-based interpolation can be only applied in frequency domain. To perform this technique, first, the impulse response of the channel is calculated by applying the IDFT over the time domain interpolated channel. After that, a low pass-filter is applied to the channel in order to remove noise and aliases. Finally, the channel is interpolated by applying a DFT to the filtered channel. DFT-based interpolation is a sophisticated technique that provides better performance than linear interpolation at the expense of introducing more complexity to the system.

For simplicity, only linear interpolation method in time and frequency domain (linear/linear) has been considered for the rest of the subsections.

6.1.4 CP, RS pattern and Nyquist limit

As specified previously, the considered SFN scenario is modelled by a 0 dB Echo channel where the receiver detects two different contributions coming from the two SFN transmitters. Since both contributions usually arrive with different delays, one of them is always considered as the main contribution and another is considered as the echo. Depending on the echo delay, the receiver considers the received signal as a useful contribution, as an interference or as a mix of both. In this aspect, the performance of the receiver is given depending on the Equalization Interval (EI). EI is the time duration during which the echo can be considered as a main or as a partial contribution. The contribution of the echo as useful or interferent is given by the weighting function w(t). As shown in Figure 26, EI has three different regions where the echo is weighted with different values.

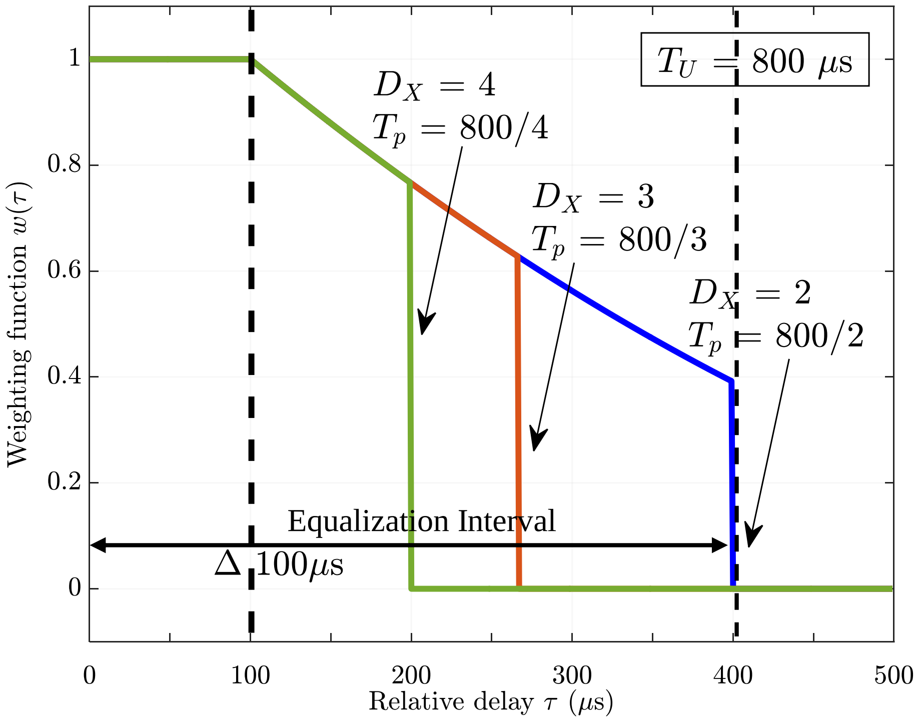

Figure 26. Weighting function and equalization interval.

- The first part where the echo is considered as a fully useful contribution is limited by the CP length. As explained in previous sections, CP is able to deal with the ISI received from different contributions, being the interference easily equalized at the receiver.
- The second part of the EI is defined as the region where the echo is considered as a useful and an interferent contribution at the same time depending on the delay with respect to the main path. This second region is limited by the CP duration and the Nyquist limit (T_p). Nyquist limit is the time duration up to a received contribution can be equalized. As mentioned in Chapter 5, T_p length depends on the D_x when a time and frequency interpolation is performed. Regarding the weighting factor, it depends on the evaluated technology and can be obtained empirically [21].
- The last part of EI is considered as the region where the echo cannot be equalized and therefore is assumed as fully interferent. It is specified as a region beyond the Nyquist limit.

In order to demonstrate the EI and the CP influence on the 5G Terrestrial Broadcast performance, some link-level simulations have been performed. Performance has been analysed by representing the variability of the QoS (BLER) with respect to the CNR depending on the echo delay. Four different echo delays related to four possible SFN scenarios have been considered: 40 µs, 80 µs, 100 µs and 200 µs.

The system has been configured with a large CP = 66.66 µs (SCS = 3.75 kHz) and a dense RS pattern (D_x = 2, D_y = 3) This parameter configuration implies a Nyquist limit of 133.33 µs.

The selected MCS is equal to 1 and the system bandwidth is 5 MHz, which combined to the SCS = 3.75 kHz implies a FFT size of 8k. According to this configuration, 5G Terrestrial Broadcast performance is shown in Figure 27.

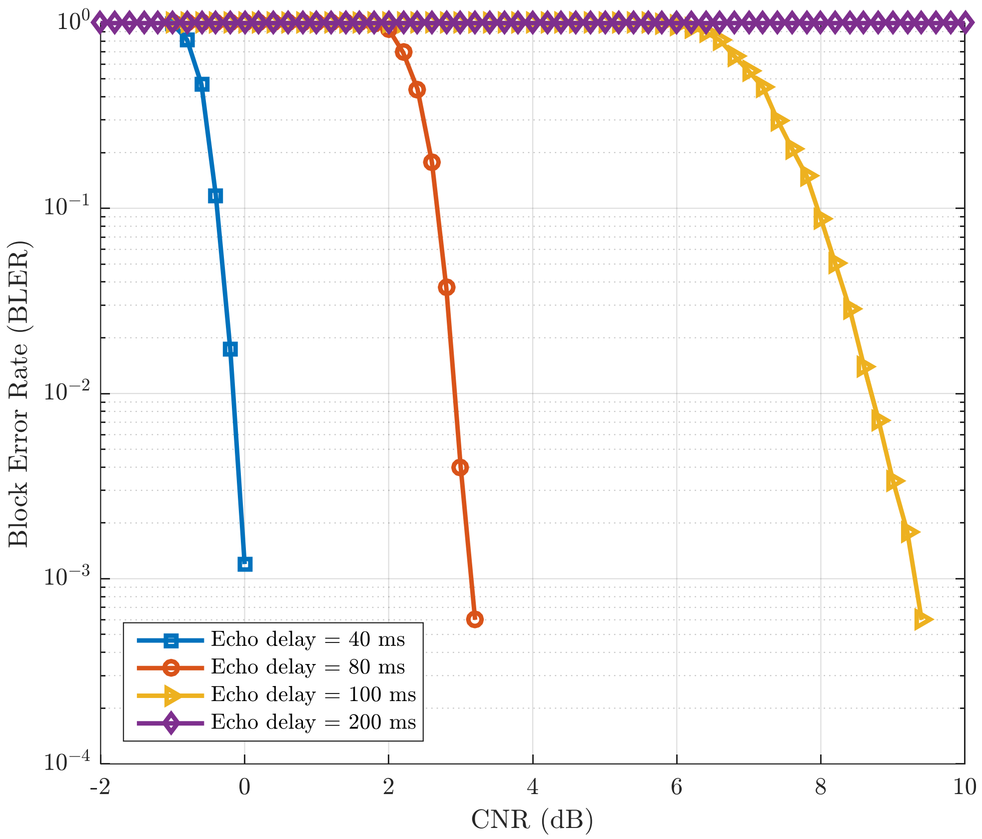

Figure 27. 5G Terrestrial Broadcast QoS vs CNR vs Echo Delay.

As it is represented in Figure 27, the performance of the system changes depending on the echo delay. On the one hand, if the echo arrives within the CP boundary, (Echo delay = 40 µs), low CNR (0 dB) is required to achieve the BLER target (10^{-3}). On the other hand, if the echo arrives beyond the CP, different degradation is introduced to the system depending on the echo delay. When the echoes arrive between the CP and the Nyquist limit (echo delay = 80 µs and echo delay = 100 µs), different degradation is introduced depending on the weighting function specified for the Equalization Interval. It should be noticed that in this region, the system is still able to receive the signal even though with a higher CNR. However, if the echo arrives beyond the Nyquist limit, the system is not able to estimate the channel in the frequency domain and therefore the required QoS cannot be achieved at any CNR value.

This analysis shows how important is the correct CP and RS pattern selection depending on the scenario where the SFN is deployed. If low ISDs are required, e.g. for urban environments, short CP can be selected. However, if higher ISDs need to be configured, e.g. for rural environments, larger CP values are required. Depending on this parameter selection, the system may be able or not to decode the received signal.

6.2 KPIs: Description and Evaluation

6.2.1 Overhead

To evaluate the selected KPI in the selected SFN scenarios, first it is necessary to analyse the overheads introduced by different physical layer parameters related to the SFN operation. In particular, the overhead introduced by the SFN Reference Signals, the Cyclic Prefix and the Guard Bands has been considered.

SFN Reference Signals

As explained in Chapter 5, the definition of specific SFN RS patterns is required to enable an accurate channel estimation in SFN environments. RS patterns are traditionally defined by the D_x and D_y parameters, which provide information about frequency and time separation between reference signals, respectively. Based on these two parameters, the overhead introduced by the reference signals is defined as:

$$OH_{RS} = \frac{1}{D_x D_y} \tag{10}$$

According to Equation 10, the overheads introduced by the 5G Terrestrial Broadcast RS patterns are calculated in Table 22.

SCS (kHz)	ISD (km)	D_x	D_y	Overhead (%)
15	5	2	3	16.66
7.5	10	2	3	16.66
3.75	20	2	2	25
2.5	30	2	2	25
1.5	100	2	2	25
1.25	60	3	2	16.66

Table 22. 5G Terrestrial Broadcast RS overhead value.

As it can be analysed, low D_x and D_y values provide a more accurate channel estimation process at the expense of introducing more overhead to the system. In particular, 5G Terrestrial Broadcast introduces considerable overheads to enable large ISDs in SFN environments. When wide SCS are selected, a less accurate RS pattern is needed in time domain (low D_y) and subsequently the overhead reaches low values, i.e. 16.66%. However, when the SCS is decreased to reach larger ISDs, a more accurate RS pattern in time domain is required and as a consequence the overhead it is increased to higher values, i.e. 25%. Regarding the frequency domain density, it is kept almost constant to provide an acceptable frequency interpolation.

These overhead values have been compared with the obtained for LTE enTV and ATSC 3.0.

SCS (kHz)	D_x	D_y	Overhead (%)
15	1	8	12.5
7.5	2	4	12.5
1.25	3	2	16.6

Table 23. LTE enTV RS Overhead Value

LTE enTV provides RS overhead values similar to 5G Terrestrial Broadcast. For wide SCS, enTV defines less dense RS patterns. As a consequence, worse channel estimation is performed at the expense of introducing less overhead to the system. With respect to the narrowest SCS configuration, the same RS pattern is configured and therefore the same overhead is introduced (16.66%).

ATSC 3.0 enables 16 possible configurations of RS patterns. As a consequence, a large and granular set of RS overheads is defined. In general, ATSC 3.0 overheads are lower in comparison with 5G Terrestrial Broadcast and LTE enTV. As shown in Table 24, only SP 3_2 and SP4_2 configurations provide overhead values similar to the introduced for the aforementioned technologies.

SP	D_x	D_y	Overhead (%)	SP	D_x	D_y	Overhead (%)
3_2	3	2	16.66	12_2	12	2	4.16
3_4	3	4	8.33	12_4	12	4	2.08
4_2	4	2	12.5	16_2	16	2	3.12
4_4	4	4	6.25	16_4	16	4	1.56
6_2	6	2	8.33	24_2	24	2	2.08
6_4	6	4	4.16	24_4	24	4	1.04
8_2	8	2	6.25	32_2	32	2	1.56
8_4	8	4	3.12	32_4	32	4	0.78

Table 24. ATSC 3.0 RS overhead value

Cyclic Prefix

As explained previously, the CP or GI is directly related to the maximum separation between transmitters (ISD) in SFN scenarios. Larger CPs enable the demodulation of echoes arriving from further transmitters and therefore to cover large coverage areas. However, CP is built as the copy of a useful OFDM symbol fraction and as a consequence introduces overhead into the system. The overhead related to the CP insertion can be calculated as:

$$OH_{CP} = \frac{T_{CP}}{T_u + T_{CP}} \quad (11)$$

where T_{CP} is the cyclic prefix duration and T_u is the OFDM symbol length. Table 25 shows the overheads associated to the different CP options in 5G Terrestrial Broadcast.

SCS (kHz)	Tu (µs)	CP (µs)	ISD (km)	Overhead (%)
15	66,66	Extended (16.66)	5	20
7.5	133,33	Extended (33.33)	10	20
3.75	266,66	Extended (66.66)	20	20
2.5	400	100	30	20
1.5	666.66	333.33	100	33.33
1.25	800	200	60	20

Table 25. 5G Terrestrial Broadcast CP overheads

As it can be seen, the reuse of the 5G numerology solution implies the definition of constant CP overheads, i.e. 20%, for the most of configurations. Thanks to it, larger ISD are enabled while keeping the same overhead values. Only the longest CP configuration, provides a higher overhead, i.e. 33.33%. This value is introduced at the expense of allowing the largest ISD of the system (100 km).

If a similar overhead calculation is performed over LTE enTV and ATSC 3.0, different conclusions can be inferred.

Despite LTE enTV provides lower CP granularity than 5G Terrestrial Broadcast, similar overhead values are obtained due the reuse of the most of configurations. Only the use of normal CP with SCS 15 kHz enables lower overhead values. The whole set of overheads is shown in Table 26.

SCS (kHz)	Tu (µs)	CP (µs)	ISD (km)	Overhead (%)
15	66,66	4.7/5.2	1.4	6.58
15	66,66	16.66	5	20
7.5	133,33	33.33	10	20
1.25	800	200	60	20

Table 26. LTE enTV CP overheads

Regarding ATSC 3.0, the definition of three possible FFT sizes for the same system bandwidth configuration leads to the definition of three possible OFDM symbol durations. For each duration, twelve possible GI values can be defined. As a consequence, up to 36 GI values and overheads can be obtained. For the present study, due to the similarity to the LTE enTV configuration, only the GI values for a 6 MHz bandwidth and FFT size 8k combination have been considered. Based on this assumption, the set of GI overheads is shown in Table 27.

Tu (µs)	GI (µs)	ISD (km)	Overhead (%)
1185.19	27.78	8.36	2.3
	55.55	16.67	4.7
	74.07	22.22	6.3
	111.11	33.33	9.4
	148.15	44.44	12.5
	222.22	66.66	18.7
	296.29	88.89	25.0
	351.85	105.55	29.7

Table 27. ATSC 3.0 GI Overheads.

Due to the large overhead introduced by the rest of GI in the FFT = 8k mode, only values from 27.78 µs up to 296.29 µs are allowed. These GI combinations lead to overheads from 2.3% up to 29.7% in order to provide coverage on cells from 8 km up to 105 km of radius. As it can be seen, despite ATSC 3.0 and 5G Terrestrial Broadcast frame structure is different, the largest overhead value related to the largest ISD is similar for both technologies: 29.7% and 33.33% respectively.

As a consequence of the impact of the overhead in the system performance, some studies like [22] have analysed the CP/GI suppression in SFN scenarios. The use of ultra-robust transmission modes may provide resilience against degradation due to ISI in SFN scenarios. As a consequence, CP/GI may be supressed in some particular conditions, e.g. when the echoes arrive with low relative power.

Frequency Guard Bands

Frequency guard bands are used to reduce Out-Of-Band Emissions (OOBE) when different RF channels are allocated within the same frequency band. Usually, two guard bands are inserted at the lowest and the highest frequencies of each RF channel – See Figure 28.

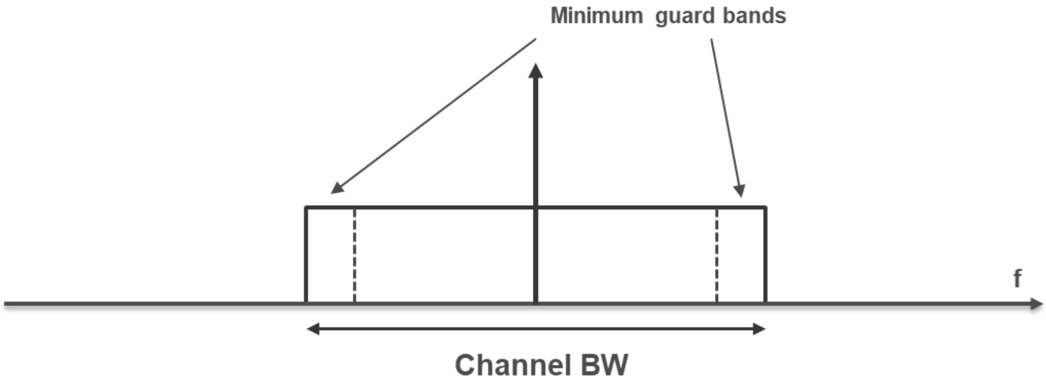

Figure 28. Guard bands in Channel BW.

The insertion of guard bands reduces the possibility of interfering RF channels each other at the expense of introducing some overheads into the system. The overhead introduced by the guard bands can be expressed as:

$$OH_{GB} = \frac{2 \cdot f_{GB}\ (Hz)}{BW\ (Hz)} \tag{12}$$

where f_{GB} is the portion of bandwidth occupied by each guard band and BW is the total system bandwidth occupied by the RF channel.

As shown in Equation 12, the impact of the guard bands depends on the selected system bandwidth. Generally, the overhead is lower when larger system bandwidths are configured due to a better use of the available frequency spectrum. However, typical TV services are delivered in low bandwidth values, e.g. 6 MHz, 7 MHz or 8 MHz, and as consequence high overheads may be introduced.

5G Terrestrial Broadcast inherits a large bandwidth granularity from 5G unicast, where values from 5 MHz up to 50 MHz can be selected for the SCS 15 kHz configuration. According to that, this master thesis considers 5 MHz and 10 MHz as potential bandwidth values used to deliver traditional TV services in 5G Terrestrial Broadcast. Regarding the overhead, [23] provides the minimum guard band size linked to all the possible 5G unicast bandwidth configurations. For 5 MHz bandwidth, each guard band occupies 242.5 kHz while for 10 MHz, frequency guard bands occupy 312.5 kHz. As a consequence, the overhead introduced by the two configurations is 9% and 6.25% respectively.

Following the same procedure, the overhead introduced by guard band has also been calculated for LTE enTV and ATSC 3.0.

With respect to enTV, the frequency guard bands size is provided at [24]. According to it, each guard band occupies 500 kHz for 5 and 10 MHz channel bandwidth and therefore a 10% of overhead is introduced.

Regarding ATSC 3.0, 6 MHz, 7 MHz and 8 MHz are the three possible bandwidth system configurations. For all of them, ATSC 3.0 defines a fixed 3% overhead value due to the use of frequency guard bands [6].

Technology	Selected BW (MHz)	Overhead
5G Terrestrial Broadcast	5	9.03%
	10	6.25 %
LTE enTV	5	10 %
	10	
ATSC 3.0	6	3%
	7	
	8	

Table 28. Summary of guard band overheads.

Table 28 summarizes the overheads introduced by the three evaluated technologies. As it can be seen, 5G Terrestrial Broadcast introduces two possible guard band overheads for the considered bandwidths. In both cases, the overhead is lower than the values provided in LTE enTV. Regarding ATSC 3.0, the DTT technology performs again as the most efficient solution introducing only a 3% overhead.

Due to the impact of the guard bands overhead in the final data rate, several studies like [25] have considered the suppression of guard bands for the new 5G Terrestrial Broadcast solution. The evaluation of this configuration might be evaluated in further studies.

6.2.2 BICM spectral efficiency

BICM spectral efficiency (η_{BICM}) indicates the number of data bits per second per Hertz needed to provide the minimum carrier-to-noise ratio (CNR). As shown in Equation 13 this KPI only considers the impact of the modulation order (Q_m) and coding (R).

$$\eta_{BICM} = Q_m \cdot R \tag{13}$$

In this study, the BICM spectral efficiency (bps/Hz) provided by the 5G Terrestrial Broadcast configuration has been calculated for a 0 dB echo channel. The performance of this technology has been compared with the values obtained for other solutions such as ATSC 3.0 and LTE enTV. The channel capacity represented as the Shannon limit has also been simulated to provide a theoretical reference.

To perform the different sets of simulations and according to the guidelines provided at Chapter 2, the following parameter configuration has been set up for the three different technologies.

Parameter configuration	ATSC 3.0	LTE enTV	5G Terrestrial Broadcast
MCS Range	2/15 up to 3/15	MCS 0 – MCS 33	MCS 0 – MCS 36
Modulation orders	QPSK, 16 NUC, 64 NUC, 256 NUC	QPSK, 16QAM, 64 QAM, 256 QAM	QPSK, 16QAM, 64 QAM, 256 QAM
LDPC length	16200 bits	Variable	Variable
Bandwidth	6 MHz	5 MHz	5 MHz
Guard Interval/Cyclic Prefix	222.22 µs	200 µs	200 µs
RS Pattern	SP 4_2	$D_x = 3$, $D_y = 2$	$D_x = 3$, $D_y = 2$
Nyquist limit	296.29 µs	266.66 µs	266.66 µs
FFT Size	8k		
Channel estimation (Time/Frequency)	Linear/Linear		
SFN Echo delay	100 µs		
QoS Criteria (BLER)	10^{-3}		

Table 29. Simulation Setup

As it can be seen in Table 29, the three technologies have been evaluated under similar parameter configurations. According to this parameter setup, the obtained BICM spectral efficiency results have been represented in Figure 29.

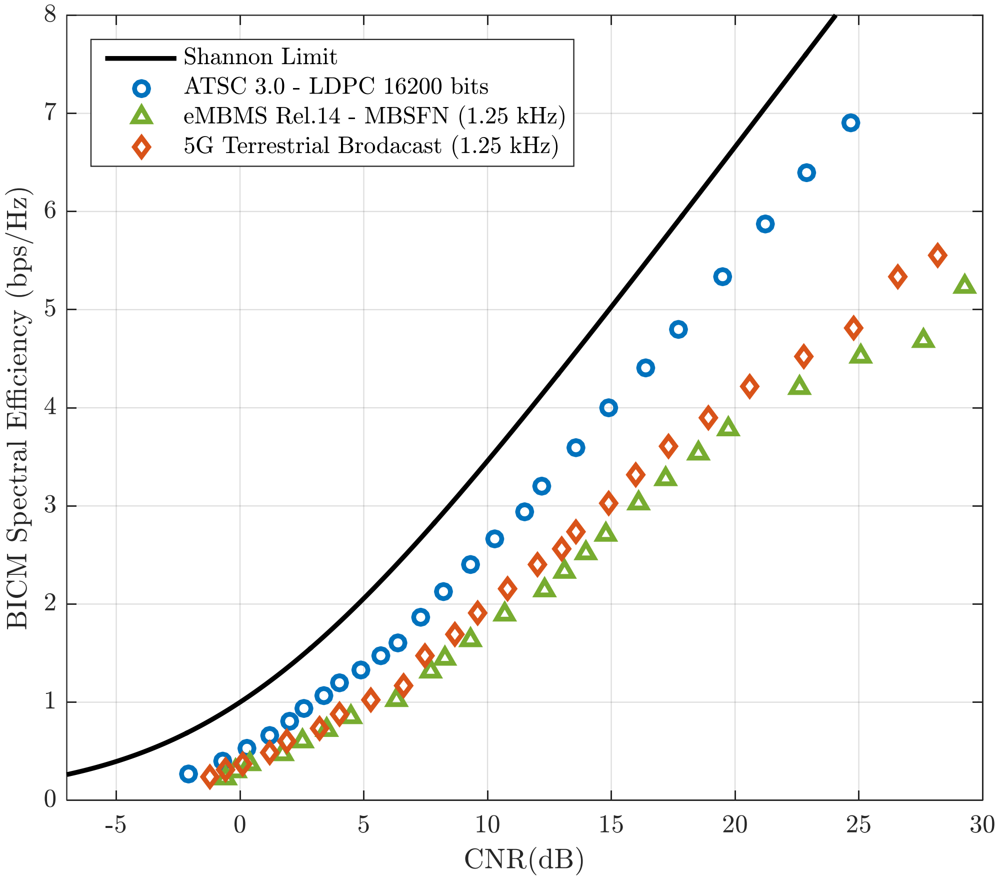

Figure 29. BICM spectral efficiency vs CNR.

As shown in Figure 29, 5G Terrestrial Broadcast provides higher BICM spectral efficiency than the LTE eMBMS solution. In particular, the gain is more noticeable for the set of MCS values in high CNR values. The main reason of this gain is the use of Low-Density Parity Check (LDPC) codes, which provide significant performance gains with respect to the Turbo-Coding (TC) techniques used in LTE.

However, ATSC 3.0 still outperforms the new 5G Terrestrial Broadcast solution for the whole range of MCS indexes. In particular, ATSC 3.0 introduces considerable gains for high CNR values due to the use Non-Uniform Constellations (NUC) and longer codeword employed for the LDPC coding technique. Some studies like [26] have demonstrated that the use of NUCs instead of traditional QAM modulations provide an important performance gain due to the geometrical signal shaping, especially for higher order constellations. It should be noted that negligible gains are obtained with QPSK, since NUC constellations does not have room for possible optimization. Regarding LDPC codewords, ATSC 3.0 uses a fixed length of 16200 bits, while the length with LDPC codes in 5G Terrestrial Broadcast is variable, reaching values between 14976 and 26112 bits depending on the MCS selection.

The highest efficiency results for each modulation order together with the corresponding CNR value have been included in Table 30. It should be noticed that other transmissions modes may provide higher BICM Spectral Efficiency values but at the expense of required CNR higher than 30 dB.

Technology	Transmission Mode	BICM Spectral Efficiency (bps/Hz)	Required CNR (dB)
ATSC 3.0	QPSK (11/15)	1.47	5.7
	16NUC (11/15)	2.93	11.5
	64NUC (12/15)	4.80	17.7
	256NUC (13/15)	6.93	24.7
LTE enTV	QPSK (MCS 9)	1.31	9.6
	16QAM (MCS 16)	2.51	14.3
	64QAM (MCS 25)	4.67	27.6
	256QAM (MCS 28)	5.23	29.3
5G Terrestrial Broadcast	QPSK (MCS 9)	1.33	8.4
	16QAM (MCS 16)	2.57	13.3
	64QAM (MCS 25)	4.81	24.8
	256QAM (MCS 30)	5.55	28.2

Table 30. BICM Spectral efficiency vs CNR results

As it can be seen, the use of LDPC codes in 5G Terrestrial Broadcast introduces higher gains for the highest MCS values with respect to LTE enTV. In addition to that, the required CNR is lower for the 5G solution, enabling transmissions for worse signal to noise conditions. In particular, a 0.33 bps/Hz gain is introduced for the highest MCS value performing with a CNR value lower than 30 dB. As mentioned before, ATSC 3.0 outperforms both solutions since gains of 1.4 bps/Hz and 1.7 bps/Hz are introduced over 5G Terrestrial Broadcast and LTE enTV respectively.

The whole set of BICM Spectral Efficiency vs CNR values linked to all the transmission modes and technologies is included in Annex B.

6.2.3 Spectral efficiency

Spectral efficiency provides the number of bps/Hz that can be transmitted for the minimum CNR considering the impact of the overhead introduced by the CP and by the RS Pattern. To calculate this KPI, BICM spectral efficiency and the overhead values calculated previously have been considered. The impact of these parameters in the spectral efficiency calculation are shown in Equation 14:

$$SpeEff = SpeEff_{RF}(SNR_{dB}) \cdot (1 - OH_{CP}) \cdot (1 - OH_{PP}) \tag{14}$$

where $SpeEff_{RF}(SNR_{dB})$ is the BICM Spectral efficiency for the required CNR, OH_{CP} the overhead introduced by the CP and OH_{PP} the overhead introduced by the pilot pattern.

According to this equation, some spectral efficiency results corresponding to the transmission modes selected previously have been included in Table 31.

Technology	**Transmission Mode**	**BICM Spectral Efficiency (bps/Hz)**	**CP Overhead (%)**	**RS Overhead (%)**	**Spectral Efficiency (bps/Hz)**
ATSC 3.0	QPSK (11/15)	1.47	18	12	1.05
	16NUC (11/15)	2.93			2.08
	64NUC (12/15)	4.80			3.41
	256NUC (13/15)	6.93			4.93
LTE enTV	QPSK (MCS 9)	1.31	20	16	0.87
	16QAM (MCS 16)	2.51			1.68
	64QAM (MCS 25)	4.67			3.11
	256QAM (MCS 28)	5.23			3.48
5G Terrestrial Broadcast	QPSK (MCS 9)	1.32	20	16	0.88
	16QAM (MCS 16)	2.57			1.71
	64QAM (MCS 25)	4.81			3.21
	256QAM (MCS 30)	5.55			3.70

Table 31. Spectral efficiency results

As it can be observed, the introduction of CP and RS overheads reduces the spectral efficiency results considerably. In particular, for 5G Terrestrial Broadcast and LTE enTV the use of a large CP and a dense RS pattern reduces the spectral efficiency in a 33%. With respect to ATSC 3.0, a reduction of around the 29% is introduced. As a consequence, ATSC 3.0 still outperforms both cellular broadcasting solutions. It should be outlined that despite such a high spectral efficiency reduction, the use of the proper CP and RS configuration is fundamental to achieve good QoS values for low CNR ranges.

6.2.4 Data Rate

Data rate is calculated as the number of data bits that can be transmitted per second for the available system bandwidth. To calculate the available bandwidth, the overhead introduced by the frequency guard bands has been considered as shown in Equation 15.

$$Data\ rate\ (bps) = SpeEff\left(\frac{bps}{Hz}\right) \cdot (BW(Hz) \cdot (1 - OH_{GB})) \tag{15}$$

where $SpeEff$ is the spectral efficiency, BW the total bandwidth and OH_{GB} the overhead introduced by the guard bands.

Following the same procedure than for the rest of KPIs, data rate is calculated for the set of ATSC 3.0, LTE enTV and 5G Terrestrial Broadcast transmission modes:

Technology	Transmission Mode	Spectral Efficiency (bps/Hz)	Bandwidth (MHz)	GP Overhead (%)	Data Rate (Mbps)
ATSC 3.0	QPSK (11/15)	1.05	6	3	6.15
	16NUC (11/15)	2.08			12.14
	64NUC (12/15)	3.41			19.87
	256NUC (13/15)	4.93			28.70
LTE enTV	QPSK (MCS 9)	0.87	5	10	3.95
	16QAM (MCS 16)	1.68			7.55
	64QAM (MCS 25)	3.11			14.03
	256QAM (MCS 28)	3.48			15.69
	QPSK (MCS 9)	0.87	10	10	7.83
	16QAM (MCS 16)	1.68			15.12
	64QAM (MCS 25)	3.11			27.99
	256QAM (MCS 28)	3.48			31.32
5G Terrestrial Broadcast	QPSK (MCS 9)	0.88	5	9	4.02
	16QAM (MCS 16)	1.71			7.79
	64QAM (MCS 25)	3.21			14.61
	256QAM (MCS 30)	3.70			16.83

	QPSK (MCS 9)	0.88	10	6.3	8.25
	16QAM (MCS 16)	1.71			16.04
	64QAM (MCS 25)	3.21			30.07
	256QAM (MCS 30)	3.70			34.67

Table 32. Data Rate results

As shown in Table 32, technologies with lower GP overhead are able to provide higher data rates in a single RF carrier. 5G terrestrial broadcast defines different GP overheads depending on the system bandwidth, being able to reduce the guard period overhead when higher bandwidths are configured. For an RF channel of 5 MHz, 5G Terrestrial Broadcast is able to provide higher data rates than LTE enTV (16.83 Mbps vs 15.69 Mbps) for a similar guard period overhead. However, ATSC 3.0 outperforms 5G Terrestrial Broadcast for a similar bandwidth, i.e. 6 MHz with 28.70 Mbps vs 34.67 Mbps. If the bandwidth is increased to 10 MHz, 5G Terrestrial Broadcast is able to provide a higher gain with respect to LTE enTV and also with respect to ATSC 3.0 (34.67 Mbps vs 31.32 Mbps vs 28.70 Mbps).

However, the main gain introduced by the 5G technology comes from enabling large carrier aggregation values. 5G NR is able to combine up to 16 RF carriers, a value quite noticeable if it is compared with the 2 RF carriers allowed by ATSC 3.0 and the 5 RF carriers enabled by LTE eMBMS. This aspect may multiply the data rate allowed by 16. However, the use of carrier aggregation is only defined for the 5G unicast solution. Further studies should determine if carrier aggregation can also be performed in the 5G Terrestrial Broadcast solution.

6.3 SFN Conclusions

As shown in this section, the proposed 5G Terrestrial Broadcast solution is able to provide a better performance than the current terrestrial broadcast solution for cellular networks, LTE enTV. The definition of lower overheads together with the use of more advance coding techniques lead to higher spectral efficiency values. In addition, the potential use of carrier aggregation techniques may offer unprecedented data rates values in the scope of cellular broadcasting. However, 5G Terrestrial Broadcast still has room for improvement since the gap to ATSC 3.0 is quite considerable. ATSC 3.0 was designed as a dedicated DTT technology and as a consequence, it is able to provide higher spectral efficiency than the cellular broadcasting solutions while introducing lower overheads. Based on this analysis, 5G Terrestrial Broadcast can considered as a very good option for the future in order to SFN while reusing the existing cellular architecture.

Chapter 7. Conclusions and Future Work

7.1 Conclusions

The present master thesis proposes design of a terrestrial broadcast solution for the physical layer of new generation of mobile communication systems, 5G NR. The performance of 5G Terrestrial Broadcast has been evaluated in specific SFN scenarios.

Previously to this design and evaluation process, the terrestrial broadcast state-of-the-art solutions, ATSC 3.0 and LTE enTV have been analysed and evaluated according to the 3GPP requirements related to the introduction of broadcast capabilities in 5G. The analysis has demonstrated that ATSC 3.0 presents some mobility limitations that impede the system to provide good performance for some transmission modes at speeds higher than 250 km/h. In addition, the deployment of a DTT technology like ATSC 3.0 in cellular environments has been considered as not efficient in terms of costs and energy. Regarding LTE enTV, some limitations in the maximum coverage allowed by the SFN operation mode have been drawn. In addition, some mobility drawbacks and the impossibility to perform MIMO transmissions have been considered as an impediment to meet the 3GPP requirements.

As a result of the gap analysis, a new terrestrial broadcast solution based in 5G NR has been proposed. Longer CPs, specific SFN RS patterns and a new 5G control region have been defined, enabling the 5G NR solution to meet the 3GPP requirement related to the coverage in SFN scenarios. In addition, the reuse of part of the 5G NR unicast physical layer has also allowed the fulfilment of the requirements related to mobility and MIMO compatibility.

Finally, the performance of the new 5G Terrestrial Broadcast solution has been analysed in SFN scenarios. The overheads introduced by the new solution, the spectral efficiency provided by the BICM chain, the total spectral efficiency and the maximum data rate values obtained in SFN deployments have been calculated. In addition, the performance of the 5G NR solution has been compared with ATSC 3.0 and LTE enTV. The comparison has shown that the new 5G Terrestrial Broadcast solution outperforms LTE enTV in all the defined KPIs thanks to the definition of lower overheads and the use of high performing coding techniques, i.e. LDPC codes. In comparison to ATSC 3.0, 5G NR Terrestrial Broadcast is still not able to obtain better performance in SFN scenarios due to the specific physical layer design introduced by the DTT solution. As main advantage, the use of carrier aggregation in 5G NR may enable larger data rates than the existing ATSC 3.0 solution in SFN scenarios.

7.2 Future Work

Considering the work performed in this master thesis as a basis, different studies could be performed in the future to extend the impact of this contribution. On the one hand, the extension of the proposed design to other layers such as the MAC or the application layer could help to the development of the final 5G Terrestrial Broadcast solution. The analysis and performance evaluation of the proposed solution in SFN scenarios could be also extended to other scenarios where mobility or ultra-high reliability conditions are required. Finally, the hardware implementation of the proposed solution could be performed by designing the corresponding chipsets and the rest of electronic components. After the design, the new 5G NR Terrestrial Broadcast design would be ready for its integration in the existing cellular network.

Annex A. Point-to-Multipoint Transmitter Blocks

This annex provides information about the physical layer mechanisms included in the transmitter blocks of ATSC 3.0, LTE eMBMS and 5G NR to perform link-level simulations.

A.1. ATSC 3.0 transmitter block

ATSC 3.0 frames are generated, transmitted and detected thanks to the use of a transmission chain that includes transmitter, channel and receiver blocks. This subsection provides a detailed description of the transmitter block and its different parts, which are shown in

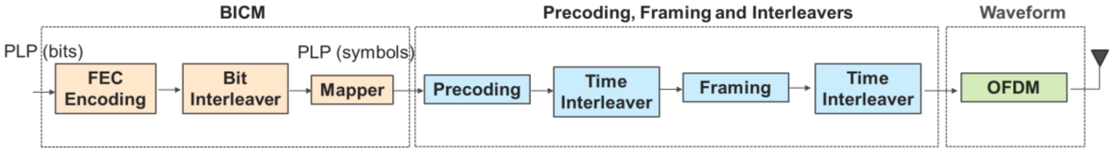

Figure 30.

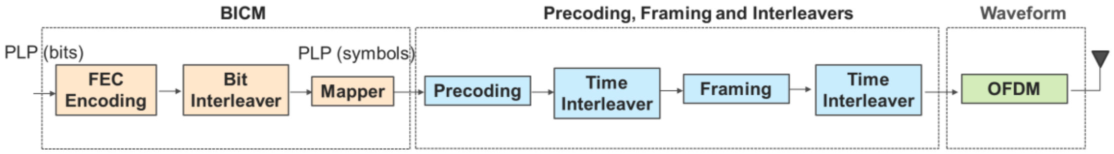

Figure 30. ATSC 3.0 transmitter block.

Within the transmitter block, three main sub-blocks can be identified:

Bit Interleaved and Coded Modulation (BICM).

In the first block of the transmission chain, encoding, bit interleaving and modulation are carried out. (See Figure 31)

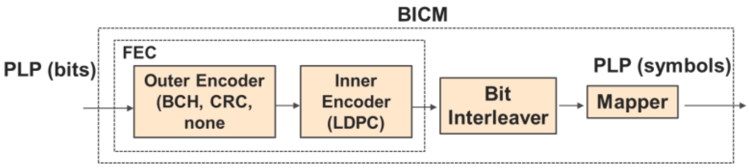

Figure 31. ATSC 3.0 BICM block chain.

First, a stream of data bits named Physical Layer Pipe (PLP), is generated and encoded by means of a Forward Error Correction (FEC) process. FEC encoding is based on outer and inner encoding techniques. For the outer encoding, three different types of codification can be selected: Bose, Ray-Chaudhuri and Hocquenghem (BCH) codes, Cyclic Redundance Check (CRC) or none encoding. BCH codes are able to detect and correct possible errors, CRC only detect errors and none encoding does not give any error protection. Regarding inner encoding, LDPC codes are used to introduce redundant information to the original stream of bits. ATSC 3.0 defines two possible LDPC code lengths: 16200 or 64800 bits. While the shortest code length, i.e. 16200 bits, gives better performance in applications where low latency and complexity are required, the longest, i.e. 64800 bits, provides better performance for the rest of cases. The level of redundancy introduced by the LDPC codes is selected by the choice of the LDPC code rates. ATSC 3.0 supports twelve different code rates, from 2/15 up to 13/15 with steps of 1/15), in order to provide granularity and flexibility for different operating modes. 2/15 is the most robust code and 13/15 is the less.

After the FEC encoding, the resultant stream of bits, which is composed of data and parity information, is introduced to the Bit Interleaver (BIL). BIL is performed to optimize the channel efficiency according to the LDPC code rate and the modulation order.

Finally, interleaved bits are mapped into complex-valued symbols by means of a modulation process. Bits can be mapped to six different constellations, i.e. QPSK, 16NUC, 64NUC, 256NUC, 1024NUC, 4096NUC, where one modulation order is uniform (QPSK) and the other five orders are non-uniform. Non-uniform constellations provide considerable performance gains in comparison with uniform constellations (QAM), especially for high modulation orders, i.e. 64NUC, 256NUC, etc. Each stream at the output of the modulation process is defined as a FEC Block.

Precoding, framing and interleaving

After obtaining the mapped symbols, time interleaving can be directly applied to FEC Blocks to introduce time diversity to the signal. If MIMO transmissions are considered, an optional precoder can be applied before the time interleaver in order to facilitate the detection process at the receiver.

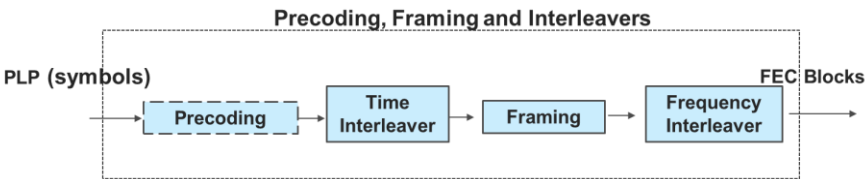

Figure 32. ATSC 3.0 Precoder, Framing and Interleavers chain.

After the time interleaving, framing and multiplexing is carried out. ATSC 3.0 frames are composed of several FEC Blocks, which are distributed in different time and frequency positions for each subframe. Commonly, frames and subframes occupy the whole frequency domain and are multiplexed in the time domain following a Time Division Multiplexing (TDM) technique. However, other multiplexing techniques such as Frequency Division Multiplexing (FDM) or Layer Division Multiplexing can also be applied [27]. Following the framing process, frequency interleaving can be optionally performed in order to avoid burst errors in the frequency domain.

Waveform

Once all the data complex symbols are distributed across the frame structure, the OFDM waveform is generated as shown in Figure 33.

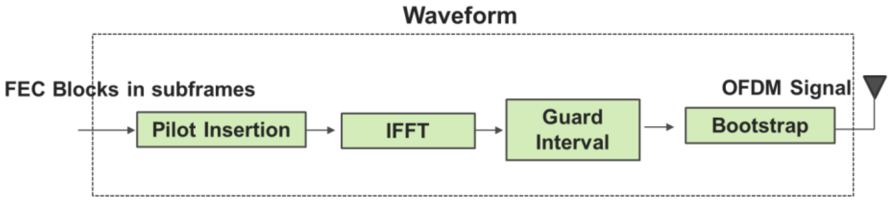

Figure 33. Waveform chain.

The OFDM signal is generated by creating the CP-OFDM waveform. CP-OFDM signal is assembled by mapping the reference signals in the corresponding resource grid positions, applying the IFFT and inserting the CP at the beginning of each OFDM symbol.

A.2 eMBMS Data Transmitter Chain

eMBMS frames and subframes are generated, transmitted and received following the traditional transmission chain. Based on that, this subsection provides a detailed description of the transmitter side in order to analyse the different physical layer mechanisms used to transmit data content through the PMCH in LTE eMBMS.

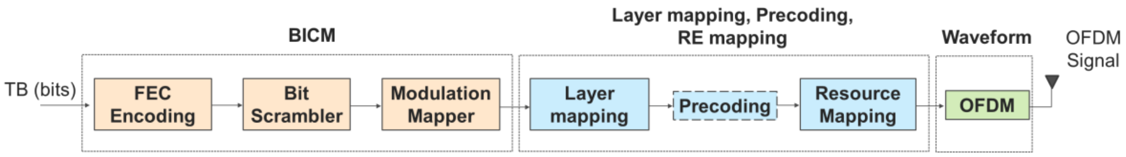

Figure 34. LTE eMBMS transmitter block.

As shown in Figure 34 the transmitter block is composed by a BICM, framing and waveform blocks.

Bit Interleaved and Coded Modulation (BICM).

First, the stream of data bits named Transport Block (TB), is generated according to the selected MCS and the available bandwidth. LTE eMBMS has thirty-four possible MCS values that are directly mapped to modulation orders. These combinations are shown in Table 33 and Table 34.

MCS Index I_{MCS}	**Modulation Order** Q_m	**Modulation Order** Q'_m	**TBS Index** I_{TBS}
0	2	2	0
1	2	2	1
2	2	2	2
3	2	2	3
4	2	2	4
5	2	4	5
6	2	4	6
7	2	4	7
8	2	4	8
9	2	4	9
10	4	6	9
11	4	6	10
12	4	6	11
13	4	6	12
14	4	6	13
15	4	6	14
16	4	6	15
17	6	6	15
18	6	6	16
19	6	6	17
20	6	6	18
21	6	6	19
22	6	6	20
23	6	6	21
24	6	6	22
25	6	6	23
26	6	6	24
27	6	6	25
28	6	6	26/26A

Table 33. LTE eMBMS MCS selection for QPSK, 16QAM, 64QAM

21	8	8	27
22	8	8	28
23	8	8	29
24	8	8	30
25	8	8	31
26	8	8	32
27	8	8	33/33A/33B

Table 34. LTE eMBMS MCS selection 256QAM

Once TBs are created, a FEC coding and segmentation process is performed. Regarding FEC coding, both outer and inner encoding are applied. The chosen outer encoding technique is CRC coding, which is applied by means of attaching CRC codes to each TB. After the CRC coding, if the TB size is greater than 6144 bits, the TB is segmented in small data packets, i.e. Code Blocks

(CB). Additionally, if segmentation is done, a second CRC sequence is attached to each CB in order to add more robustness to the system.

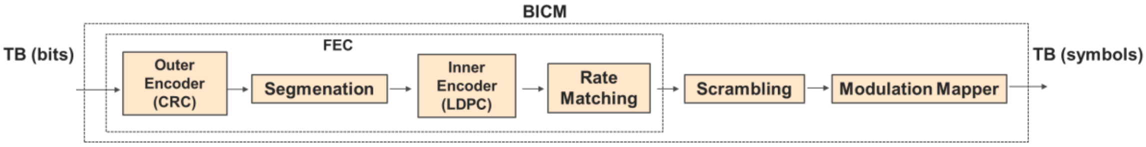

Figure 35. LTE eMBMS BICM block.

After segmentation, the inner coding is performed. LTE eMBMS introduces the use of turbo coding (TC) technique, which is applied with a fixed CR of 1/3. In order to achieve the final CR associated to the selected MCS and TBS, rate matching block is also performed. Rate matching consists of a bit interleaving, circular buffering and bit puncturing or repeating process. Finally, all the CBs located at the rate matching output are concatenated to create a single stream of bits. Once the stream of bits is created, bit scrambling can be applied in order to add diversity against possible burst errors. Then, bits are mapped to complex-valued symbols. LTE eMBMS has four different constellations available: QSPK, 16QAM, 64QAM and 256QAM.

Layer mapping and resource mapping

After the symbol modulation, complex symbols are mapped and precoded depending on the number of transmitter antennas and the number of layers.

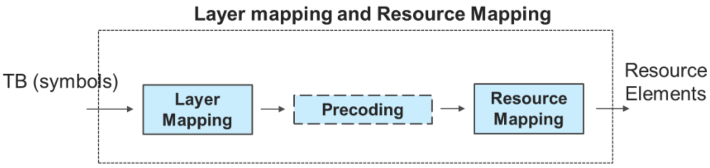

Figure 36. LTE eMBMS Layer mapping block.

Since LTE eMBMS does not allow multi-antenna transmissions, layer mapping and precoding is a transparent process. Resource allocation is done by means of mapping the complex symbols to different positions in the resource grid.

Waveform

Once the complex symbols are allocated, OFDM modulation is performed to spread the information across frequency and time domain. To that end, IFFT as well as reference signals and cyclic prefix insertion are performed.

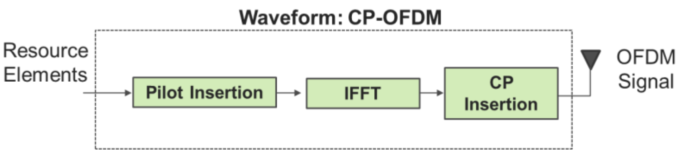

Figure 37. LTE eMBMS Waveform block.

First, RS are inserted in all time and frequency positions not occupied by the data symbols. As explained in the previous subsection, depending on the subcarrier spacing and CP type, different RS patterns are defined. After that, IFFT is performed over a fixed number of subcarriers that depend on the subcarrier spacing and the available bandwidth. Finally, to generate the CP-OFDM waveform, CP is inserted at the beginning of the useful OFDM symbol. Once it has been generated, the content is ready to be transmitted.

A.3 5G NR Data Transmitter Chain

5G NR data content is transmitted and received over the PDSCH channel following the traditional transmission chain, which is composed by transmitter, channel and receiver. In order to analyse the different physical layer mechanisms, this subsection provides a detailed description of the 5G NR transmitter block.

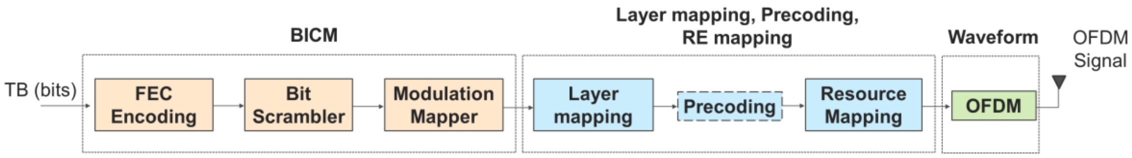

Figure 38. 5G NR transmitter block.

5G NR transmitter is very similar to the one used in LTE eMBMS. In it, three main blocks are defined: BICM, layer and RE mapping and waveform.

Bit Interleaved and Coded Modulation (BICM)

As for eMBMS, BICM block consists of a codification, bit scrambling and modulation process. Transport block remains as the initial stream of data bits transmitted in a subframe. TB size depends on the number of transmitted RB and the MCS selection. The number of RB is calculated depending on the available system bandwidth and the RB size.

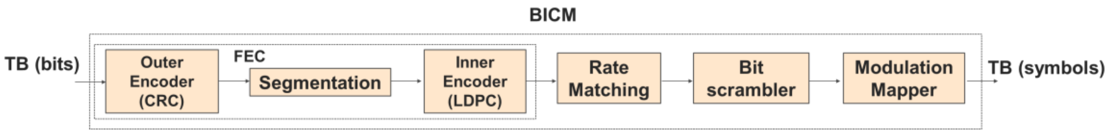

Figure 39. 5G NR BICM block.

Regarding the MCS selection, 5G NR introduces the definition of thirty-seven MCSs values, which are linked to fixed coding rate and modulation order combinations. These MCSs values together with their equivalent spectral efficiency are shown in Table 35 [28].

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate x [1024] R
0	2	120
1	2	157
2	2	193
3	2	251
4	2	308
5	2	379
6	2	449
7	2	526
8	2	602
9	2	679
10	4	340
11	4	378
12	4	434
13	4	490
14	4	553
15	4	616
16	4	658
17	6	438
18	6	466
19	6	517
20	6	567
21	6	616
22	6	666
23	6	719
24	6	772
25	6	822
26	6	873
27	6	910
28	6	948
29	8	682.5
30	8	711
31	8	754
32	8	797
33	8	841
34	8	885
35	8	916.5
36	8	948

Table 35. 5G NR MCS values

Once TB size has been specified, FEC coding is applied. First, some CRC codes are attached to the TB. The output of the outer coding is segmented depending on the TB+CRC length and the LDPC base graph selected. If TB plus CRC is larger than 3840 bits (Base Graph 1) or 8448 bits (Base Graph 2), segmentation is performed. In that case, the TB is divided in different CBs, which are outer coded again by adding a CRC part to each CB. After that, bits are inner coded by means of applying LDPC codes. LDPCs add redundant information to the data bits of each CB depending on the selected numerology and MCS. LDPCs are more efficient than TC technique used in eMBMS. LDPC output is introduced to the rate matching block, where the exact code rate is obtained by means of a bit selection, pruning and bit interleaving process. After that, all the code blocks are concatenated to create the final stream of bits.

Finally, bits are scrambled and mapped to complex-valued symbols depending on the modulation order. 5G NR has four different modulation orders available: QPSK, 16QAM, 64QAM, 256QAM, which are selected depending on the MCS choice.

Layer Mapping, precoding and RE mapping

Once the complex-valued symbols are obtained, layer mapping and precoding are applied depending on the number of layers and the number of transmitter antennas.

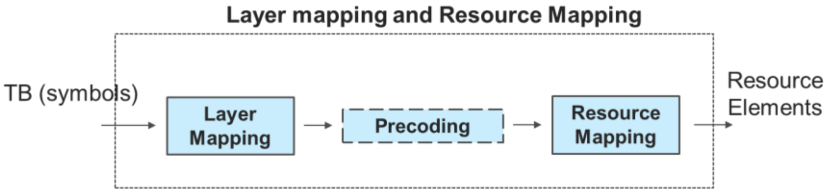

Figure 40. 5G NR layer and RE mapping blocks.

5G NR enables to transmit up to 8 layers by means of MIMO antenna configurations. If MIMO configuration is used, precoding techniques can be applied to the transmitted signal in order to facilitate the detection process at the receiver. After the precoding, complex symbols are mapped in their corresponding time and frequency positions across the resource grid. This process is known as Resource mapping.

Waveform

Once the RE mapping is performed, the OFDM signal is generated by creating the CP-OFDM waveform. CP-OFDM generation process is similar to eMBMS, where the waveform is generated by mapping the reference signals in the corresponding resource grid positions, applying the IFFT and inserting the CP at the beginning of each OFDM symbol.

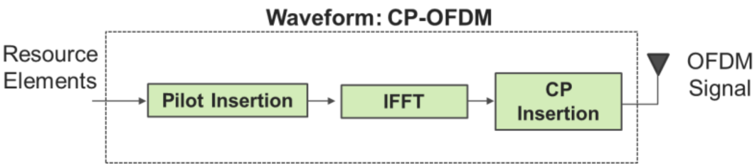

Figure 41. 5G NR Waveform Generation.

Annex B. BICM Spectral Efficiency Results

This annex includes the BICM Spectral Efficiency vs CNR results obtained for ATSC 3.0, LTE enTV and 5G NR. The configuration used to obtain all the results is described in Chapter 6.

B.1 ATSC 3.0

Modulation Order (Q_m)	Code Rate	BICM Spectral Efficiency (bps/Hz)	CNR (dB) BW= 6 MHz
QPSK	2/15	0,27	-2,10
	3/15	0,40	-0,70
	4/15	0,53	0,30
	5/15	0,67	1,20
	6/15	0,80	2,00
	7/15	0,93	2,60
	8/15	1,07	3,40
	9/15	1,20	4,00
	10/15	1,33	4,90
	11/15	1,47	5,70
16QAM	4/15	1,07	4,00
	5/15	1,33	5,20
	6/15	1,60	6,40
	7/15	1,87	7,30
	8/15	2,13	8,20
	9/15	2,40	9,30
	10/15	2,67	10,30
	11/15	2,93	11,50
64QAM	4/15	1,60	6,40
	5/15	2,00	8,10
	6/15	2,40	9,60
	7/15	2,80	11,10
	8/15	3,20	12,20
	9/15	3,60	13,60
	10/15	4,00	14,90
	11/15	4,40	16,40
	12/15	4,80	17,70
256QAM	4/15	2,13	9,00
	5/15	2,67	10,80
	6/15	3,20	12,70
	7/15	3,73	14,60
	8/15	4,27	16,20
	9/15	4,80	17,90
	10/15	5,33	19,50
	11/15	5,87	21,20
	12/15	6,40	22,90

	13/15	6,93	24,70

Table 36. BICM Spectral Efficiency results for ATSC 3.0

B.2 LTE enTV

MCS Index (I_{MCS})	Modulation Order (Q_m)	Code Rate	BICM Spectral Efficiency (bps/Hz)	CNR (dB) BW = 5 MHz	CNR (dB) BW = 10 MHz
0	1384	0,12	0,23	-0,90	-0,60
1	1800	0,15	0,30	0,20	-0,20
2	2216	0,18	0,37	0,70	0,40
3	2856	0,24	0,47	2,10	1,70
4	3624	0,30	0,60	2,70	2,50
5	4392	0,37	0,72	3,80	3,50
6	5160	0,43	0,85	4,70	4,50
7	6200	0,52	1,02	6,30	6,30
8	6968	0,58	1,15	7,60	7,50
9	7992	0,67	1,32	9,80	9,60
10	7992	0,33	1,32	7,50	7,70
11	8760	0,37	1,45	8,20	8,30
12	9912	0,41	1,64	9,20	9,30
13	11448	0,48	1,89	10,60	10,70
14	12960	0,54	2,14	12,00	12,30
15	14112	0,59	2,33	13,50	13,10
16	15264	0,64	2,52	14,60	14,30
17	15264	0,42	2,52	14,10	14,00
18	16416	0,46	2,71	14,90	14,80
19	18336	0,51	3,03	16,10	16,10
20	19848	0,55	3,27	17,20	17,20
21	21384	0,59	3,53	18,50	18,50
22	22920	0,64	3,78	19,90	19,70
23	25456	0,71	4,20	22,30	22,60
24	27376	0,76	4,52	24,60	25,10
25	28336	0,79	4,68	27,90	27,60
26	30576	0,85	5,05	>30	>30
27	31704	0,88	5,23	>30	>30
28	31704	0,66	5,23	28,90	29,30
29	32856	0,68	5,42	>30	>30
30	35160	0,73	5,80	>30	>30
31	36696	0,76	6,05	>30	>30
32	39232	0,82	6,47	>30	>30
33	40576	0,85	6,70	>30	>30
34	42368	0,88	6,99	>30	>30

Table 37. BICM Spectral Efficiency for LTE enTV

B.3. 5G NR Terrestrial Broadcast

MCS Index (I_{MCS})	Modulation Order (Q_m)	Code Rate	BICM Spectral Efficiency (bps/Hz)	CNR (dB) BW = 5 MHz	CNR (dB) BW = 10 MHz
0	2	0,12	0,23	-1,1	-1,2
1	2	0,15	0,31	-0,4	-0,6
2	2	0,19	0,38	0,2	0,1
3	2	0,25	0,49	1,5	1,2
4	2	0,30	0,60	2,2	1,9
5	2	0,37	0,74	3,3	3,2
6	2	0,44	0,88	4,4	4
7	2	0,51	1,03	5,9	5,3
8	2	0,59	1,18	6,8	6,6
9	2	0,66	1,33	8,5	8,4
10	4	0,33	1,33	6,6	6,6
11	4	0,37	1,48	7,5	7,5
12	4	0,42	1,70	8,8	8,7
13	4	0,48	1,91	9,7	9,6
14	4	0,54	2,16	10,8	10,8
15	4	0,60	2,41	12,1	12
16	4	0,64	2,57	13,6	13,3
17	6	0,43	2,57	13	13
18	6	0,46	2,73	13,6	13,6
19	6	0,50	3,03	14,9	14,9
20	6	0,55	3,32	16,1	16
21	6	0,60	3,61	17,5	17,3
22	6	0,65	3,90	18,9	18,9
23	6	0,70	4,21	20,7	20,6
24	6	0,75	4,52	23,2	22,8
25	6	0,80	4,82	27	24,8
26	6	0,85	5,12	>30	>30
27	6	0,89	5,33	>30	>30
28	6	0,93	5,55	>30	>30
29	8	0,67	5,33	26,8	26,6
30	8	0,69	5,55	28,2	28,2
31	8	0,74	5,89	>30	>30
32	8	0,78	6,23	>30	>30
33	8	0,82	6,57	>30	>30
34	8	0,86	6,91	>30	>30
35	8	0,90	7,16	>30	>30
36	8	0,93	7,41	>30	>30

Table 38. BICM Spectral Efficiency for 5G NR Terrestrial Broadcast.

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