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Point-to-Multipoint services on Fifth-Generation Mobile Networks

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Abstract

Point-to-multipoint services over mobile networks have always been of interest to several verticals. They are not only limited to the delivery of television, but other applications such as Internet of Things (IoT), Vehicular-to-Everything, Public Warning Services (PWS); which can efficiently leverage the capacity that the use of point-of-multipoint provides. In this regard, mobile networks had their first version of a Broadcast/Multicast extension in 3G, known as Multicast/Broadcast Multimedia Services (MBMS). However, this technology was considered limited in technical and economical terms and did never successfully take off. The 4G Long Term Evolution (LTE) version, enhanced MBMS (eMBMS), provided the much needed enhancements by listening to the requirements of the broadcast industry. Broadcasters, specially in Europe, see in this technology a potential terrestrial broadcast standard able to provision point-to-multipoint services for both rooftop antennas, pedestrian devices and moving vehicles. Yet, the requirement of New Radio based point-to-multipoint mode was defined in the early stages of 5G, but it was not until Release 17 that this requirement started to get addressed, in the form of 5G Multicast Broadcast Services (5MBS). These point-to-multipoint mobile standards compete against the existing European standard DVB-T2 and the American ATSC 3.0, already deployed commercially. It remains to be seen what will happen to the lower band of the UHF, which is currently allocated to primary broadcast services in ITU region 1 and an agenda topic for the World Radio Congress of 2023. In other regions, part of the band has been allocated to 5G communications.

This dissertation covers the state-of-the-art in LTE eMBMS Release 14, also known as Enhanced Television Services (ENTV). ENTV provided a suite of radio and core enhancements that made eMBMS into a viable terrestrial broadcast standard. The latest iteration of this technology is known as LTE-based 5G Broadcast; even though it is not New Radio or 5G Core based. To bridge this gap, research efforts by academia, public and private enterprises evaluated how to provide a 5G-based solution for point-to-multipoint services. The most notable effort in this regard is the Horizon 2020 project 5G-Xcast, which ran from 2017 to 2019. 5G-Xcast provided several architectural solutions, from the content delivery perspective down to air interface specifics; providing new waveforms based on New Radio and Network Functions interoperable with a Release 15 5G Core. The findings are summarized in this thesis. Two examples of eMBMS applied to different verticals are included in the thesis, one for the use of eMBMS in industrial environments, and the other using eMBMS as a PWS technology.

Providing point-to-multipoint services as another cellular service poses some problems, as the standardization process of eMBMS showed: the broadcast infrastructure is different than the cellular one. Having a waveform that is suited for both scenarios is a difficult endeavour. The thesis provides a new perspective into this problem: Having existing Terrestrial Broadcast standards and infrastructure be the point-to-multipoint solution of 5G, where mobile operators and broadcasters collaborate together. This is defined in the dissertation as Convergence of Terrestrial and Mobile Networks. The technologies chosen to be converged together were ATSC 3.0 and 5G; using the existing Release 16 framework known as Advanced Traffic Steering, Switching and Splitting (ATSSS). ATSSS is a series of procedures, interfaces, new Network Functions, to allow the joint use of a 3GPP Access Network alongside a non-3GPP one, like Wi-Fi. However, the use of ATSSS for cellular plus broadcast brings challenges, as the ATSSS technology was not designed to be used with a unidirectional access network like ATSC 3.0. These limitations are described in detail, and an architectural proposal that overcomes the limitations is proposed. This solution is based on Quick UDP Internet Connections (QUIC), and how to provide Convergent Services (i.e File Repair and Video Offloading) is shown.

The thesis concludes with a description of Release 17 5MBS, including the new concepts introduced. 5MBS features the capacity of switching between unicast, multicast and broadcast; depending on the service addressed, the geographical location of the users, and the capability of the RAN infrastructure targeted. In order to evaluate 5MBS, a performance study of the use of multicast inside the 5G Core has been carried out. The 5MBS prototype was developed as part of the VLC Campus 5G laboratory, using the commercial software Open5GCore which provides the libraries and Network Functions to deploy your own 5G Private Network in testing environments. The system model of the experiment is formed by a video server, connected to the Open5GCore and the 5MBS enhanced functions; which will deliver the content to an emulated RAN environment hosting virtual gNBs and devices. The results obtained reinforce the objective of the thesis, positioning point-to-multipoint as a scalable way to deliver live content.

Resumen

Los servicios punto-a-multipunto sobre redes móviles siempre han sido de interés para diversos verticales. No solo está limitado al envío de televisión, otras aplicaciones tales como Internet de las Cosas, Vehicular-a-Todo, o Sistemas de Alarma Pública (SAP) también pueden explotar eficientemente la capacidad de las conexiones punto-a-multipunto. La primera versión de servicios Broadcast/Multicast para redes móviles ocurrió en 3G, definido como Multicast Broadcast Multimedia Services (MBMS). Sin embargo, esta tecnología se considera limitada en términos económicos y tecnológicos, y nunca llegó a despegar con éxito. La versión 4G Long Term Evolution (LTE), enhanced MBMS (eMBMS), trajo las mejoras necesarias escuchando los requerimientos de la industria televisiva. Las operadoras de televisión, especialmente en Europa, ven en eMBMS un candidato potencial para el envío de televisión terrestre, capaz de proveer servicios de radiodifusión a antenas fijas, dispositivos a nivel de calle, o vehículos en movimiento. Aún así, el requerimiento de un modo punto-a-multipunto basado en 5G New Radio no se cumplió hasta la llegada de la Release 17, a pesar de estar definido durante las etapas de estandarización 5G. Este modo se llama 5G Multicast Broadcast Services (5MBS). Estos estándares móviles punto-a-multipunto compiten contra los existentes estándares de Televisión Digital Terrestre, tales como el Europeo DVB-T2 o el Americano ATSC 3.0, ya desplegados comercialmente. Queda observar lo que ocurrirá a la parte baja de la banda UHF, la cual sigue asignada a servicios de radiodifusión primarios en la región 1 de la ITU, pero es un punto en la agenda del World Radio Congress de 2023. En otras regiones, parte de la banda ya ha sido asignada a comunicaciones 5G.

Esta disertación cubre el estado del arte en LTE eMBMS Release 14, también conocido como Enhanced Television Services (ENTV). ENTV trajo un conjunto de mejoras, tanto a nivel radio como a nivel de núcleo, que transformó a eMBMS en un estándar de televisión terrestre completo. La última versión de esta tecnología se denomina LTE-based 5G Broadcast; pero no usa New Radio ni el núcleo 5G. Para proveer una solución nativa 5G de servicios punto-a-multipunto, hubo investigación en entornos académicos y colaboraciones público-privada. La iniciativa más notable en este aspecto fue el proyecto del Horizon 2020 5G-Xcast, que transcurrió de 2017 a 2019. 5G-Xcast produjo varias soluciones a nivel de arquitectura, desde la perspectiva de provisión de contenidos, nuevas funciones de red interoperables con el núcleo 5G, hasta modificaciones a la interfaz aire basada en New Radio. Los hallazgos del proyecto están descritos en esta tesis. La tesis incluye dos ejemplos de eMBMS aplicados a verticales diferentes, una para el uso de eMBMS en entornos industriales, y otra presentando eMBMS como un sistema SAP.

Incluir servicios punto-a-multipunto como un modo adicional celular trae algunos desafíos, como ya mostró la estandarización de eMBMS: las redes de radiodifusión terrestre y las redes celulares son muy distintas entre ellas. Encontrar una forma de onda viable para ambas infraestructuras es complejo. Esta tesis ofrece un punto de vista distinto al problema: un escenario de colaboración entre cadenas televisivas y operadores móviles, donde la infraestructura de radiodifusión y móvil son compartidas. Este concepto se ha definido como Convergence of Terrestrial and Mobile Networks. Las tecnologías elegidas para converger son ATSC 3.0 y 5G, usando el Advanced Traffic Steering, Switching and Splitting (ATSSS). ATSSS está compuesto de una serie de procedimientos, interfaces, funciones de red, para permitir el uso compartido de un acceso 3GPP con uno non-3GPP, como Wi-Fi. Sin embargo, el uso de ATSSS para juntar radiodifusión y celular no es trivial, ya que ATSSS no fue diseñado para enlaces radio unidireccionales como ATSC 3.0. Estas limitaciones son descritas en detalle, y una propuesta para solventarlas también está incluida. La solución se basa en Quick UDP Internet Connections (QUIC), y se usa como ejemplo para la provisión de Convergent Services (File Repair y Video Offloading).

La tesis concluye con una descripción de Release 17 5MBS, con los nuevos conceptos introducidos. 5MBS es capaz de cambiar entre unicast, multicast y broadcast; dependiendo del servicio, la ubicación geográfica de los usuarios, y las capacidades de la infraestructura móvil involucradas. Para evaluar 5MBS, se ha realizado un estudio de prestaciones, basado en comunicaciones multicast dentro del núcleo de red 5G. Este prototipo 5MBS forma parte del laboratorio VLC Campus 5G, y utiliza el software comercial Open5GCore como base del desarrollo. El modelo de sistema para la experimentación esta formado por un servidor de vídeo, que se conecta al Open5GCore y a las funciones de red mejoradas con funcionalidades 5MBS. Estas funciones de red envían el contenido mediante punto-a-multipunto a un entorno radio y terminales simulados. Los resultados obtenidos resaltan el objetivo principal de la tesis: las comunicaciones punto-a-multipunto son una solución escalable para el envío de contenido multimedia en directo.

Resum

Els serveis punt-a-multipunt sobre xarxes mòbils sempre han sigut de interès per a diversos verticals. No sols està limitat a l'enviament de televisió, altres aplicacions com ara Internet de les Coses, Vehicular-a-Tot, o Sistemes d'Alarma Pública (SAP) també poden explotar eficientment la capacitat de les connexions punt-a-multipunt. La primera versió de serveis Broadcast/Multicast per a xarxes mòbils va ocórrer en 3G, definit com Multicast Broadcast Multimèdia Services (MBMS). No obstant això, aquesta tecnologia es considera limitada en termes econòmics i tecnològics, i mai va arribar a enlairar amb èxit. La versió 4G Long Term Evolution (LTE), enhanced MBMS (eMBMS), va portar les millores necessàries escoltant els requeriments de la indústria televisiva. Les operadores de televisió, especialment a Europa, veuen en eMBMS un candidat potencial per a l'enviament de televisió terrestre, capaç de proveir serveis de radiodifusió a antenes fixes, dispositius a nivell de carrer, o vehicles en moviment. Tot i així, el requeriment d'una manera punt-a- multipunt basat en 5G New Radio no es va complir fins a l'arribada de la Release 17, malgrat estar definit durant les etapes d'estandardització 5G. Aquest mode es diu 5G Multicast Broadcast Services (5MBS). Aquests estàndards mòbils punt-a-multipunt competeixen contra els existents estàndards de Televisió Digital Terrestre, com ara l'Europeu DVB-T2 o l'Americà ATSC 3.0, ja desplegats comercialment. Queda observar el que ocorrerà a la part baixa de la banda UHF, la qual segueix assignada a serveis de radiodifusió primaris a la regió 1 de la ITU, però és un punt en l'agenda del World Radio Congress de 2023. En altres regions, part de la banda ja ha sigut assignada a comunicacions 5G.

Aquesta dissertació cobreix capdavanter en LTE eMBMS Release 14, també conegut com Enhanced Television Services (ENTV). ENTV va portar un conjunt de millores, tant a nivell de ràdio com a nivell de nucli, que va transformar el eMBMS en un estàndard de televisió terrestre complet. La última versió d'aquesta tecnologia es denomina LTE-based 5G Broadcast; però no fa servir New Ràdio ni el nucli 5G. Per a proveir una solució nativa 5G de serveis punt-a-multipunt, va haver-hi investigació en entorns acadèmics i col·laboracions pública i privada. La iniciativa més notable en aquest aspecte va ser el projecte del Horizon 2020 5G-Xcast, que va transcórrer del 2017 a 2019. 5G-Xcast va produir diverses solucions a nivell d'arquitectura, des de la perspectiva de provisió de continguts, noves funcions de xarxa interoperables amb el nucli 5G, fins a modificacions a la interfície aire basada en New Radio. Les troballes del projecte estan descrits en aquesta tesi. La tesi inclou dos exemples de eMBMS aplicats a verticals diferents, una per a l'ús de eMBMS en entorns industrials, i una altra presentant eMBMS com un sistema SAP.

Incloure serveis punt-a-multipunt com una manera addicional cel·lular duu alguns desafiaments, com ja va mostrar l'estandardització de eMBMS: les xarxes de radiodifusió terrestre i les xarxes cel·lulars són molt diferents entre elles. Trobar una forma d'ona viable per a totes dues infraestructures és complex. Aquesta tesi ofereix un punt de vista diferent al problema: un escenari de col·laboració entre cadenes televisives i operadors mòbils, on la infraestructura de radiodifusió i mòbil són compartides. Aquest concepte s'ha definit com Convergence of Terrestrial and Mobile Networks. Les tecnologies triades per a convergir són ATSC 3.0 i 5G, usant el Advanced Traffic Steering, Switching and Splitting (ATSSS). ATSSS està compost d'una sèrie de procediments, interfícies, funcions de xarxa, per a permetre l'ús compartit d'un accés 3GPP amb un non-3GPP, com a Wi-Fi. No obstant això, l'ús de ATSSS per a adjuntar radiodifusió i cel·lular no és trivial, ja que ATSSS no va ser dissenyada per a per a enllaços ràdio unidireccionals com ATSC 3.0. Aquestes limitacions són descrites detalladament, i una proposta per a solucionar-les també està inclosa. La solució es basa en Quick UDP Internet Connections (QUIC), i s'usa com a exemple per a la provisió de Convergent Services (File Repair i Vídeo Offloading).

La tesi conclou amb una descripció de Release 17 5MBS, amb els nous conceptes introduïts. 5MBS és capaç de canviar entre unicast, multicast i broadcast; depenent del servei, la ubicació geogràfica dels usuaris, i les capacitats de la infraestructura mòbil involucrades. Per a avaluar 5MBS, s'ha realitzat un estudi de prestacions, basat en comunicacions multicast dins del nucli de xarxa 5G. Aquest prototip 5MBS forma part del laboratori VLC Campus 5G, i utilitza el programari comercial Open5GCore com a base del desenvolupament. El model de sistema per a l'experimentació està format per un servidor de vídeo, que es connecta al Open5GCore i a les funcions de xarxa millorades amb funcionalitats 5MBS. Aquestes funcions de xarxa envien el contingut mitjançant punt-a-multipunt a un entorn ràdio i terminals simulats. Els resultats obtinguts ressalten l'objectiu principal de la tesi: les comunicacions punt-a-multipunt són una solució escalable per a l'enviament de contingut multimèdia en directe.

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Chapter 1

Introduction

This chapter introduces the thesis work. First, it provides an insight on the concept of Point-to-multipoint services and the benefits they provide, not only from a Multimedia and Entertainment perspective but also considering other verticals; with special mention of the current lower UHF band spectrum situation and the current status of the Terrestrial Broadcast standards. Then, the 5G Standard is introduced, explaining the main innovations that drove this mobile generation, and a description of the new components at the Radio Access Network (RAN) and Core. The last two sections of Chapter 1 are focused, respectively, in the thesis overall objective description and a list of the outcomes derived from the dissertation and scientific output produced.

1.1 Point-to-multipoint Services

Point-to-multipoint is the ability to reach several users with a single transmission. It is characterized by the scalability that it provides, where the costs to deliver data to the audience does not scale with the number of users. This is particularly relevant when the data gets delivered over means that are valuable and scarce, such as the radio-frequency spectrum. There are services or verticals that have their whole business model or utility based on the ability to perform point-to-multipoint, such as radio, push-to-talk communications or television; while others see point-to-multipoint as a way to optimize their resource usage. Nowadays, as further population of the world gets connected to the internet, both at their home and in their devices, the global infrastructure is put to test as the traffic used is monotonously increasing. Mobile video traffic is estimated to be 69% of all worldwide data traffic, and it is being expected to be grow up to 79% in 2027 [1]. Mobile Network Operator (MNO)s face an ever increasing challenge to cope with the demand, as the technologies used on-top of their infrastructure have been designed for dense and urban based, point-to-point, unicast data transmissions, thus they are not scalable when delivering the same content to many users at the same time. To confront this problem, MNOs have bought more and more spectrum, lobbied together for more spectrum allocation, and research ways to optimize the spectral efficiency of the air interface [2] and reuse as much as possible the spectrum they have e.g. Multiuser Multiple Input Multiple Output (MIMO). Yet, very few of them see in point-to-multipoint a viable solution for resource optimization and reduced energy consumption. This resource optimization and energy reduction directly translates into economic savings, as disclosed in [3]. Terrestrial Broadcast is considered the less contaminant way to deliver multimedia video, compared to cable or satellite [4]. In Australia, the dynamic switching between unicast to broadcast is implemented by Telstra; and mostly used for the delivery of sports events [5]. Adoption-wise, only three operators have incorporated enhanced Multicast Broadcast Multimedia Services (eMBMS) in their catalogue [6]. Earlier versions of mobile point-to-multipoint technologies during the 2000s [7] were introduced and launched commercially, but did not gain traction, due to several reasons including specific hardware, additional spectrum licensing and product subscription cost, low manufacturer adoption and the quality of phone screens not meeting consumer satisfaction [8].

But the Multimedia and Entertainment sector is not the only one that can benefit from point-to-multipoint capabilities. The advantages it brings also benefit other verticals, such as Public Warning System (PWS), Internet of Things (IoT), Vehicular To Everything (V2X). By incorporating multicast or broadcast into the existing mobile infrastructure, aforementioned sectors would gain a scalable, sustainable and far-reached delivery method for their needs. Each vertical has different motivations to use point-to-multipoint services, in detail: PWS is characterized by its uncertainty of events, where natural disasters or terrorist attacks can happen anywhere and whenever. In order to alert the population, a system capable to reach as much people as possible is desired. Not only that, but special groups, such as firefighters, military or policemen benefit from a push-to-talk communication to keep each other informed. In this sense, having a technology already supported by widespread cellular devices can be helpful as the infrastructure to deliver both Public Warning and special applications to privileged groups is already there. On the other hand, the IoT ecosystem is characterized by a series of diverse capabilities equipment that report their status and forward their metrics or captured data back to a centralized platform for posterior processing. The number of devices scale directly with their capabilities: the number of IoT devices expected in a network scale inversely with the computing power and data throughput of them.

An IoT network could be composed of thousand of outdoor sensors which will report their accumulated data periodically then go to sleep most of the time. In contrast, a camera surveillance system that constantly sends its video feed to a central room is much more constrained in terms on how many cameras it can support, and the quality of the video feeds. For IoT, point-to-multipoint can be used to address a large amount of devices that require common data, for example, a reliable file delivery of a firmware update. In the thesis, two systems have been designed that leverage eMBMS, for the PWS and IoT verticals, they are described in Chapter 2. Last, V2X also makes use of point-to-multipoint. Ideally, a moving vehicle could inform all surrounding vehicles of its position, by sending its location to the closest cellular transmitter, which will forward it to every connected car in the vicinity. This is known as Cooperative, Connected and Automated Mobility (CCAM). It is clear how this type of communication benefits from having a multicast mode, as the location data only needs to be delivered once per cell, instead of having to use additional radio resources to address all nearby cars. Additionally, this type of multicasting the location of nearby cars slightly improves the latency, as the cellular receivers in the cars do not to search for its own information in the radio frames, saving some decoding time, but when talking about moving cars, this reduction could prevent road accidents.

1.1.1 Terrestrial Broadcast

Point-to-multipoint or broadcast has been associated traditionally with Terrestrial Broadcast services or Linear TV. It is characterized by being a curated point-to-multipoint transmission (that is, the consumer cannot choose the content), usually delivered via High-Power High-Tower (HPHT) infrastructure to rooftop antennas and then using common infrastructure in the buildings to each household. Broadcast is one of the most popular and extended telecommunication services in the world; with an estimated 1700 million households in 2022 having a television [9]. Broadcasters business model is publicly funded or revolves around the delivery of advertisement in their transmissions, sometimes both. Broadcasters are usually involved in every step of the broadcast content workflow, usually capturing and covering events, producing their own content and distributing it to the masses in many forms; including cable, terrestrial, satellite or internet. There is the possibility that they do not own their transport infrastructure to deliver the multimedia content: the sites, towers, cable or satellite links is rented from a third party, known as Neutral Hosts. Publicly funded broadcasters or Public Service Media (PSM) play a role of sharing cultural, diversity and human values to large audiences. European PSMs also have to ensure that their content follow some guidelines and is regulated [10].

For example, every member state of the EU must guarantee that 50% of their broadcasted audiovisual content is made in Europe. Another important aspect of Terrestrial Broadcast is the standard use to deliver this content. The situation worldwide in this regard is fragmented, as different part of the world developed their own broadcast standard without any interoperability with other systems in mind. Most of these standards deployed worldwide can be grouped in 4 main groups:

- Digital Video Broadcasting (DVB). The first version of a Terrestrial Broadcast standard made by DVB is DVB-T, published in 1997. The main feature was the inclusion of Orthogonal Frequency-Division Multiplexing (OFDM) waveforms and the multiplexation of compress video and audio together, using MPEG-2 as video format [11]. It is mostly deployed and used in Europe. A revised version, DVB-T2, was published in 2009; which offered more than 30% capacity gain when compared to DVB-T. DVB-T2 motivation was to support the High Definition TV (HDTV) formats and being able to dedicate part of the waveform to different television services, in the form of Physical Layer Pipe (PLP)s. DVB-T2 was also made future proof thanks to the addition of Future Extension Frame (FEF), supporting other type of frames, even non-DVB, to be multiplexed in time with DVB-T2 ones.

- Advanced Television Systems Committee (ATSC). ATSC provided the standard with the same name in 1996. Unlike DVB-T, ATSC uses a waveform based on the modulation of vestigial bands. ATSC is deployed in most of North America and South Korea. Several revisions to the standard were introduced since 1997. ATSC 2.0 brought many immersive services like hybrid TV by using internet connections to enhance the delivery, but was never commercially launched. All of the improvements researched in this standard were included in the third revision, ATSC 3.0., with a big update to its physical layer [12] and features a full IP framework. The first release of ATSC 3.0 was done in 2016. Deployments are on-going in South Korea which adopted the standard, broadcasters in United States can optionally update their ATSC network, and Jamaica has fully adopted the standard and it is actively deploying transmitters. In terms of technical performance, it provides higher throughput than DVB-T2. A noteworthy effort of ATSC 3.0 is the creation of a specialist group, to evaluate core technologies applied to the ATSC 3.0 framework. The goal is to provide an standardized core formed by Network Functions, protocols and interfaces, to manage diverse services than simple Linear TV, including data offloading, IoT services, and provision of multimedia to vehicles.

- Integrated Services Digital Broadcasting Terrestrial (ISDB-T) is the Terrestrial Broadcast standard provided by the Japanese institute NHK, in 2003. It features a OFDM modulation, and a tight partition of the UHF band where each channel is divided in 13 segments, with one of them allocated to the mobile broadcast standard 1seg. Depending on the required bandwidth of the service, a video will use more or less segments. For example it is expected that a HDTV video makes use of the 12 segments available. The standard is mostly deployed in Japan. Brazil adopted the standard and performed a series of modifications, and release a first version in 2009, with the name ISDB-T international. This version of ISDB-T is deployed mostly in South American countries, favoured for its good compromise in cost, bandwidth, mobility and coverage.

- Digital Terrestrial Multimedia Broadcast (DTMB) is a combination of three standards made by Chinese academia. It was adopted by China in 2006, and it is now being deployed in several Asian countries and Cuba. Technology wise, it is based on Time Domain Synchronization OFDM. Compared to other standards, instead of leaving an empty guard band between radio channels, it uses a random noise sequence to allow for faster signal acquisition. A second generation Terrestrial Broadcast standard based on DTMB, called DTMB-A, is released in 2013. Performance wise, DTMB-A has similar throughput than DVB-T2.

Equipment manufacturers would prefer to have a single broadcast standard worldwide, as it would reduce costs in terms of equipment and increase the interoperability of receiver devices. This is particularly important in regards to Mobile Broadcasting, or broadcast standards that instead of targeting fixed roof-top antennas, their goal is to reach moving pedestrians with devices at street level. Manufacturers do not see a feasible business to integrate every broadcast standard in the world inside a miniaturized device that they want to as simple as possible to reduce costs. In this regard, they see an opportunity in a 3GPP based Mobile Broadcasting standard, such as eMBMS, to provide a truly global broadcast standard. Broadcasters also want a broadcast standard flexible enough to accommodate roof-top reception, mobile devices and moving vehicles; while leveraging all the effort done by 3GPP to polish their specifications. More details regarding eMBMS can be found in Chapter 2. Related to this, China Broadcasting Network notified in a public 3GPP mailing list that their new broadcast standard will be fully 5G based.

Broadcasters have a large technical debt they have been accumulating over the years. As seen above, most of the broadcast standards used were created in the 2000. The only broadcast standard which is fully IP is ATSC 3.0. The rest uses very specific interfaces and protocols to deliver content, such as the DVB-

ASI to deliver the MPEG-2 streams. Most of the equipment used in the central broadcast studios is monolithic hardware, with only one functionality, and expensive to upgrade or replace. In contrast, the IT sector experienced a modernization in the provision and deployment of services and components. First, the softwarization of hardware functions provided a way to use Commercial off the Shelf (CotS) equipment in professional environments, compared to hardware-specific monolithic solutions. This derived in a reduction the cost to upgrade, maintain or replace pieces of equipment. Then, the virtualization of components applied an abstraction layer which separated the computing and storage resources from the actual function themselves, allowing hardware components to be used for several functions at the same in a flexible way. These ideas evolved into what we know today as the cloud, where an undetermined number of hardware resources is abstracted and interconnected from the services themselves. In this environment, functions can be instantiated or destroyed based on user demand, saving energy and computing resources. The final step in this cloudification of services is the adaptation of the programming itself of the functions into was it known as cloud-native programming [13], where the functions are modularized into stateless microservices, fully leveraging the advantages of cloud computing. Some broadcast manufacturers already provide software solutions to encode multimedia content following broadcast standards, but to truly leverage the advantages of the cloud, the standard itself must be designed to exploit the advantages of cloud computing, e.g. 5G is a standard designed with cloud deployments in mind.

1.1.2 Broadcast Spectrum

Spectrum is one of the most important factors in the deployment, adoption and coverage of wireless services. For broadcasting, the situation is even more critical. The Radio Regulations of 1947 [14]allocated the band between 470-960 MHz to broadcasting services. Effectively, the band that the majority of International Telecommunications Union (ITU) member countries used for Terrestrial Broadcasting is 470-862 MHz. The band coexists with many other services, including fixed wireless, radio astronomy, Public Protection and Disaster Relief (PPDR)... Several decades later, the next notable broadcast spectrum revision for Region 1 (affecting Europe, Russia, part of Middle East and Africa) was introduced in [15], where alongside plans for the Analog Switch-Off (ASO), Ultra-High Frequency (UHF) band 790-862 MHz was allowed for primary International Mobile Telecommunications (IMT) mobile technologies. Afterwards, in the WRC-12 [16], it was decided that the UHF segment of 694-790 was going to be used for IMT mobile transmissions, with a deadline of 2020 for EU members. As an example of the current situation in Spain, the 694-790

MHz band is destined for 5G deployments, with the auctions performed in July 2021; while the 790-862 MHz band is being exploited for 4G services. Overall, the total frequency quantity for broadcasting has decreased by 168 MHz.

Broadcasters face themselves with a problem, where the users demand higher quality such as Ultra High-Definition (UHD), 4K, High Dynamic Range (HDR) or High Frequency Range (HFR) while the total spectrum to do so is shrinking. Additionally, during WRC-2019 [17] several radio services stakeholders demanded more spectrum in the lower band of 700 MHz, i.e. the frequency band of 470 to 694 MHz [18]. In detail, military (between extra 80 to 120 MHz), PPDR (two channels of 10 MHz each) and mobile IMT services (at least, 120 MHz) asked the WRC for further spectrum allocation in region 1. As a consequence, the ITU decided to add an agenda item for upcoming WRC-23, known as Agenda Item 1.5 (AI 1.5). As part of this work, ITU will review the spectrum use and needs in the whole 470 to 960 MHz band and do an assignation review based on the input of ITU members. To gather and perform compatibility studies in AI 1.5, an ITU Task Group named TG 6/1 was formed , congregating all stakeholders with interests in the sub-1 GHz band. Their outcomes will be presented in the Conference Preparatory Meeting (CPM) scheduled for March 2023 [19]; where a consolidated report will be drafted alongside potential solutions to AI 1.5. Nevertheless, the European Union (EU) Radio Spectrum Policy Group (RSPG) has guaranteed that the band for 470-694 MHz in the EU will be allocated to Digital Terrestrial Television (DTT) until 2030. The European Spectrum Agenda for 2030 and beyond will be revised based on WRC-23 output.

MNOs see in this segment of the spectrum, from 600 to 694 MHz, an opportunity to deploy new networks with high coverage and good indoor reception with a relatively small amount of sites. For example, the total cost of ownership of a 4G network based on a 700 MHz carrier is six times lower than one based on 2100 MHz [20]. When compared to the mid or high frequency bands, the total capacity provided by this low band sites is lower, but they are better suited to provide connectivity in places where no connection is available i.e solving the Digital Divide [21]. An important segment in this regard is the mMTC or IoT, where a massive amount of low bandwidth, outdoor or indoor sensors, require connectivity. Yet, the BNOs and the MNOs could coexist, if the spectrum allocation were more flexible and based on local licenses based on regions. In [22], a stakeholder analysis for the UHF bands is carried out; and the authors conclude that a new figure of a Band Manager, between the local authorities and enterprises, could be beneficial to adapt the needs of BNOs and MNOs, and favour new emerging business models of coexistence or convergence. The current regulatory framework of spectrum licensing will not be enough for broadcast to innovate as a scalable delivery method for many different verticals.

1.2 The 5G standard

5G is the latest iteration of cellular networks specifications. This technology was made as a candidate for the IMT-2020 process, where the ITU provides a series of requirements that the new cellular standard must fulfil. Any technology that passes through the ITU revision will gain access to the new IMT-2020 spectrum bands to be deployed. 3GPP, the main standardization body for cellular networks, has a history of aligning new mobile generations with new IMT technologies contest. The first version of 5G was released in 2017, with the definition of the new air interface, New Radio (NR); the new RAN, NG-RAN, formed by next generation Node B (gNB)s; and the transport layer provided by the 5G Core [23]. Release 15, the first release of 5G, is characterized by its staggered deployment phases: a first option, known as Non-StandAlone (NSA), was introduced to ease the migration and adoption of 5G by the MNOs. NSA is characterized by the reliance on the 4G Evolved Packet Core (EPC) to provide the core functionalities, while the user plane of the air interface uses NR and the control plane signalling is delivered over LTE interfaces. By doing this, 3GPP considers that the enhanced Mobile BroadBand (eMBB) delivery mode; a requirement of the IMT-2020 process, is fulfilled. eMBB communications are characterized by the maximum amount of capacity that the air interface, NR, can provide. Note that another IMT-2020 communication mode, massive Machine Type Communications (mMTC), was also covered with Release 15, but it is based on a LTE solution. Release 16 addressed the last IMT-2020 air interface requirement, Ultra Reliable Low-Latency Communications (URLLC) communications. Other feature introduced in Release 16 was Advanced Traffic Steering, Switching and Splitting (ATSSS), providing a framework for the joint use of non-3GPP access network and a 3GPP one. Chapter 3 of the thesis leverages this functionality to provide Convergent Services with a Broadcast and a Cellular Network. Aforementioned solutions were packaged together and sent to the ITU, which reviewed the specifications and its performance, and agreed in February 2021 that 5G NR was, in fact, a 5G technology [24]. Regarding the air interface, NR most relevant characteristics are the new frequency bands used. They are divided in two broad groups, sub-6 GHz communications and millimetric Wave (mmWave), starting at 28 GHz. NR allows up to 800 MHz of maximum bandwidth in mmWave for a single user. An additional feature is the inclusion of transmitters and receivers featuring a large number of antennas, in what is defined as Massive MIMO. The propagation properties of these high frequency transmissions are compensated with the inclusion of Beamforming in the transmitter antennas, focusing the energy radiating from the cell in a narrow beam that keeps rotating, leveraging antenna array physical properties. Release 17 is an iteration and revision of previous features, and introduction of new ones; one of them, 5G Multicast Broadcast Services (5MBS), has a chapter dedicated to it in this thesis, Chapter 4. Release 17 will end in December of 2022. From Release 18 onwards, the specifications of 5G are known as 5G-Advanced, following a similar terminology to the 4G era. Looking forward, it is expected that the first release of 6G will occur in 2027, during Release 21; as it was said previously, to align with the IMT-2030 revision process.

1.2.1 5G Core

The 5G Core experimented of the most disruptive innovations from its 4G counterpart. The design of the 5GC was influenced by the current architecture of the leading IT enterprises. The goal was to catch-up the mobile core network into the cloud era. To do so, several technologies and concepts affected the standardization of the 5GC: Control and User Plane Separation (CUPS), Software-Defined Networking (SDN), Network Function Virtualization (NFV), Service Based Architecture (SBA) and Network Slicing. In detail: CUPS, was introduced in LTE Release 14, and it is the first step in the modularization of the EPC. Several logical components in the EPC where separated by functionality into the control plane and the user plane. The motivation is to improve scalability, as some components that may need to upgraded only because constraints in the user plane while the control aspect can still handle the load. 5G fully embraced this principle, with a control plane fully separated composed of Network Function (NF)s separated from the user plane, which only features the User Plane Function (UPF). Follow up to this, SDN is the ability for a network to be configured by software. SDN is composed by a SDN controller, following open standards such as OpenFlow, which can define the forwarding and routing rules of a low level SDN-capable equipment dynamically, according to different criteria or user input. In this regard, 3GPP incorporates one SDN interface, the N4 reference point, which connects the UPF to the Session Management Function (SMF). In a broad sense, the SMF is able to modify the behaviour of the packets entering the UPF, performing a high-level version of SDN. Other case of SDN inside of the 5GC is when new instances of the NFs forming the Control Plane are created, and need to be connected to the rest of the core. This connection and forwarding rules can be delivered in real time depending on the status of the network via SDN instructions. This leads into the next innovation, NFV, the virtualization of network functions. Thanks to the modularization of CUPS and the ability to dynamically configure the forwarding of components, the entities forming the 5GC can be virtualized, that is, they can be deployed as Virtual Machine (VM)s or containers and still perform their functionality without user input. This is known as orchestration. However, it is not scalable to deploy point-to-point interfaces for every new instance of a Network Function that the system needs. This is where SBA can provide an advantage. SBA is based on the communication between stateless NFs using HTTP/2 requests over a common bus. NFs will expose their services using a standardized Application Programming Interface (API) and subscribe depending on their needs to other NFs services dynamically. When new NFs are instantiated, they register with the Network Repository Function (NRF), which monitors the status and health of every instance running in a 5GC. New NFs only need to known how to locate this NRF, which can point them into how to find the other NFs e.g. using Domain Name System (DNS) resolution. The last foundation of the 5GC is the concept of Network Slicing. Network Slicing is able to segment the network into isolated slices, which can be optimized to perform and serve certain verticals. For example, a Network Slice for an eMBB service and another for a URLLC service can coexist, each of them with specific versions of the components which have been optimized for the service. Note that the implementation of Network Slices is not defined by 3GPP and left by manufacturer decision, but security guarantees should be follow, such as service isolation between slices. Note that all aforementioned innovations and concepts are optional, and 5GC providers can still choose to provide their Core Network based on monolithic hardware entities and use reference point interfaces to interconnect each NF.

The 5GC SBA representation can be seen in Figure 1.1. The control plane is composed of the following NFs: Network Slice Selection Function (NSSF), Network Exposure Function (NEF), NRF, Policy Control Function (PCF), Unified Data Management (UDM), Aplication Function (AF), Authentication Server Function (AUSF), Access and Mobility Function (AMF), SMF and UPF. Each NF task is detailed next:

- NSSF does the Network Slice selection when an UE attaches to the network, based on the service requested or other metrics such as International Mobile Subscriber Identity (IMSI) of the user. In detail, NSSF will direct the user to the appropriate AMF that servers its slice.
- NEF exposes the capabilities of the network towards untrusted applications outside of the network. It acts as a firewall, ensuring that incoming connections only can reach what they need and not the whole 5GC.

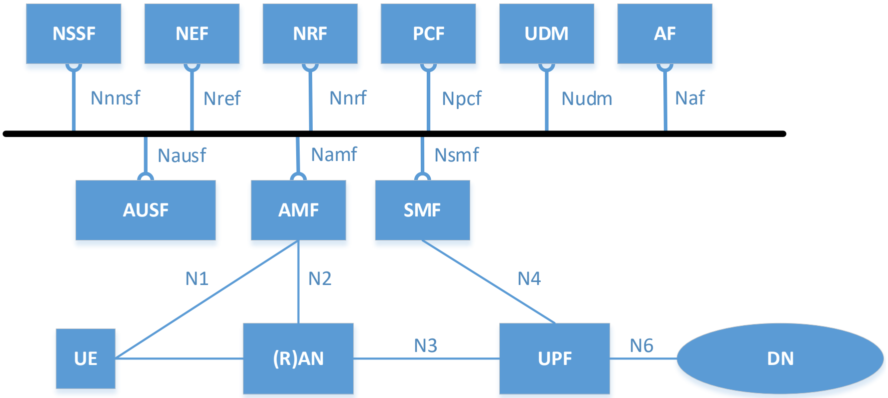


Figure 1.1: Release 15 SBA Architecture of the 5GC [23]. The Control Plane functions are connected to a common bus, which delivers HTTP/2 requests between NFs. The User Plane is composed of the UPF, which handles the data forwarding into the RAN and the public internet, while applying QoS profiles to incoming flows

- NRF registers the newly instantiated NFs, monitors their health (e.g their computational load), and decides which NFs to interconnect between them. For example, a URLLC specific AMF will ask the NRF where to find an appropriate URLLC SMF, and the NRF will provide the address to subscribe to their services.

- PCF stores the policies that affect the UE traffic. SMF will request for the policies of a given user and forward them into the UPF.

- UDM does store user data, such as encryption keys or any type of special policy information.

- AF performs any function that requires direct access to other NFs in real time, without interfacing to the NEF.

- AUSF authenticates the user in the network, verifying that they have a subscription in the database and allowing it to attach. It will request UDM for this information

- AMF is tasked with the control plane messaging between the 5GC and the devices. It holds the geographical and Radio Resource Control (RRC) status of the UEs, and monitors the status of the gNBs that form the RAN.

- SMF does the session management of the users, applying the policy from the PCF, and forwarding these instructions to the UPF over the N4 interface. Each PDU session i.e. outgoing connection will have its own entry in the SMF. The SMF will also assign the IPs to the users so they can be reached by external entities.

- UPF performs the routing of the packets inbound to the RAN via N3 and outbound to the public network over N6. It is also tasked with the QoS handling, based on the PCF rules which has been forwarded by the SMF over the N4 interface.

Overall, the modularization of the 5GC makes it ideal for the decomposition of its functions into microservices for posterior migration into a cloud-native environment. However, the UPF remains a discrete entity with a reference point interface, N4. There have been efforts in Release 17 [25] to start separating the functionality of the UPF into independent and stateless functions so some of them can eventually join the SBA paradigm.

1.2.2 NG-RAN

The main element of the NG-RAN is the gNB. It is the bridge between the user and the 5G Core. The protocol stack implemented is composed of the following stack [26]:

- Service Data Adaptation Protocol (SDAP). This layer is new to 5G, and is tasked with the Quality of Service (QoS) handling, since the new Protocol Data Unit (PDU) sessions now consist both of radio bearers and a QoS flow.

- Packet Data Convergence Protocol (PDCP). This protocol handles the packets in terms of reordering, duplicate packet detection, user data transfer, header compression and decompression.

- Radio Logical Channel (RLC). The RLC layer defines the transmission types for the UE data flows. There are three modes currently: Acknowledged Mode, where each packet reception must be verified, and in case of failure, it is retransmitted. Unacknowledged Mode, where no verification is needed for packets. The last mode is Transparent Mode where no headers are introduced and packets are just forwarded to the bottom layers.

- Medium Access Control (MAC). The MAC controls the parametrization of the Physical Layer, and the mapping of the different flows into logical channels into physical ones, including the scheduling according to the QoS Flows. This layer is also responsible for the retransmissions, according to the instructions of the overlaying RLC channel.

- Physical Layer (PHY). This step is where the NR standard is applied, creating the waveform according to the MAC layer parametrization and depending on the physical channel being radiated.

The main innovation that brings is the separation of its functionality, which incentivise the deployment of Cloud-RAN topologies. In detail, this is known as the CU-DU separation. gNBs are divided into two main components, segmenting the protocol stack between them. The gNB Control Unit (gNB-CU), performs the SDAP and PDCP, while the gNB Distributed Unit (gNB-DU) is tasked with the RLC, MAC and PHY. This can be further divided, as the PHY layer can be moved into a Remote Radio Head (RRH) closer to the user, but it is optional. The motivation is that, the higher layers of the gNB are less constraint in terms of bandwidth and latency, so they can be centralized and far away from the physical transmitter; but the lower layers are more demanding so they benefit from the reduced latency as they are closer to the actual transmitter, or even implement it inside. The gNB can even be further divided, applying the CUPS principle, into the gNB-CU-CP and the gNB-CU-UP, to independently scale the required components. For example, the gNB-CU-UP is expected to be much computing intensive than the gNB-CU-CP, since it handles the user data flowing into the air. If necessary, new instances of gNB-CU-UP can be spun up and connected to the same gNB-CU-CP, without needing to deploy a full gNB-CU. By separating and modularizing the functionality, the gNB-CU can reside in a central cloud, where computing resources are allocated dynamically, and the number of gNB-DU can also vary depending on user demand, their geographical location and physical infrastructure deployment.

A notable effort to highlight in terms of NG-RAN interoperability is the O-RAN Alliance. It was formed in 2018 and the goal is to provide specifications for interfaces and components inside the gNB, depending if they are real time or not, to encourage the interoperability between manufacturers who choose to follows this set of specifications. O-RAN is a set of extensions to the existing 3GPP gNB standards; which takes in mind the application of Machine Learning to optimize operations based on detection anomaly and quality prediction. I.e Traffic Steering of users in faulty cells into neighbours to ensure service continuity. These applications are known as xApps [27].

1.3 Objectives

The **main objective** of this dissertation is **to evaluate and design the inclusion of point-to-multipoint services in the latest cellular generation, 5G, at an architecture and radio level**, while providing a clear background and existing limitations of the current solutions, including 4G and 5G technologies, to do so. The main goals are focused on assessing the challenges and limitations of existing Mobile Broadcast services, and to design a solution that will overcome them. The following are the partial objectives of the dissertation:

- Evaluate the current State-of-the-Art for Mobile Broadcast technologies, while monitoring the newest developments in the mobile standardization group, both for the 4G and 5G versions of the technology. The limitations of eMBMS Release 14 have been analysed as part of this objective.

- Design of the 5G RAN that is able to support point-to-multipoint services. The use of Multicast/Broadcast is considered from two different perspectives, one where it is a top-down service, as such, it is seen as a service itself, so the 5G Core Network is involved in the service provisioning. The other aspect of Multicast/Broadcast is the resource optimization of using one signal to address several users. A revised synchronization scheme to enable Single Frequency Networks (SFN) is also included.

- Deliver a blueprint of the Mobile Core Network capable of supporting point-to-multipoint services, that is interoperable with the existing 5G Core Network. The proposed Core Network is based on new Network Functions and related interfaces while being compatible with the Service Based Architecture. For Terrestrial Broadcast, an alternative version is also provided, with the minimal Network Functions which is suitable to be deployed as a Network Slice.

- Study of convergence scenarios between existing Terrestrial Broadcast standards and 5G mobile networks. Different levels of convergence between infrastructure offering Convergent Services are possible. This point has addressed the case of Convergence between ATSC 3.0 and 5G Networks, both at Core and RAN; provided a set of limitations using current 3GPP technology, and presented an architecture based on Quick UDP Internet Connections (QUIC) that can overcome the limitations.

- Development of a functional prototype implementing a partial set of the 5MBS functionality suite, in order to evaluate the performance and features. The prototype has been developed in the VLC Campus 5G laboratory, which features a Release 15 compliant and software based 5G Core named Open5GCore. This program has been used as a basis to host the enhanced Network Functions to support point-to-multipoint communications.

1.4 Structure and contributions

The thesis is structured in five chapters. The three main Chapters of this thesis are 2, 3 and 4. These chapters are introduced with a technological background of the topic disclosed in, followed by in-depth explanation of the thesis contribution in the form of limitation analysis, proposed architecture to overcome the limitations, or an experiment to evaluate the performance. Chapter 5 concludes the thesis with a summary of the work done and future research lines of these topics. The key contributions of the main chapters of the thesis are the following:

Chapter 2: Pre-Release 17 Mobile Broadcasting

The thesis identified a list of limitations of the current Mobile Broadcasting solution, eMBMS; alongside several improvements to solve a partial number of them. However, to fully overcome the current limitations, a new architecture, which followed a ”blank slate” design, was done as part of a H2020 European Research project. The main contribution of this chapter is the 5G-Xcast Core and RAN architectures, a joint effort between many partners, to provide point-to-multipoint services in 5G. Two different alternatives for the 5G Core are presented, one more disruptive compared to previous eMBMS architectures and the other more similar, to ease the possible migration roadmap. Derived from this, several papers have been produced and published: [J1], [J2],[J4]. [C2] describes a new synchronization scheme produced in this thesis, based on the 4G eMBMS one, but applied to the 5G RAN and targeting Terrestrial Broadcast services. This chapter also reports on two solutions derived from the thesis work, where eMBMS is applied to the IoT and the PWS verticals. These results were published in two scientific publications: [C1] and [J3]. The work done here was divided across two projects, [R1] and [R2].

Chapter 3: Convergence of Terrestrial and Mobile Networks

The thesis proposed an alternative perspective on the Mobile Broadcasting problem. Instead of creating Broadcast/Multicast modes included in the cellular technology; this chapter studies the collaboration avenues between a Broadcast Network and a Mobile Network. This concept is defined as Convergence of Terrestrial and Mobile Networks. The analysis was performed to the ATSC

3.0 broadcast standard and 5G mobile standard. To do so, the use of existing standardized tools to provide joint communications between 3GPP and non-3GPP networks was studied. The existing technology, known as ATSSS, was not designed to cover unidirectional networks such as broadcast ones. A list of challenges were derived as result of this study, that hindered the untrusted (i.e two different entities looking to collaborate) convergence of ATSC 3.0 and 5G. To overcome the challenges, a modified convergent architecture, based on QUIC, has been designed. This architecture can solve most of the limitations and enable convergent Broadcast-Mobile networks. This work has derived in two patents, [P1], which covers the inclusion of ATSC 3.0 functionality as Trusted NFs of the 5G Core; and [P2], describing the QUIC Convergent solution, which as been submitted and waits for pending status. In the same vein, [C3] describes the ATSSS limitations and introduces the QUIC Convergent solution.

Chapter 4: Release 17 Mobile Broadcasting & Evaluation

The thesis summarized the work in Release 17 to standardize point-to-multipoint communications in 5G, which is known as 5MBS. 5MBS is a set of new NFs, protocols, interfaces, delivery modes, RAN transmission modes, logical channels, among others; that enable the provisioning of multicast and broadcast communications. The dissertation includes the performance evaluation of this technology, where a partial set of 5MBS features were included in the VLC 5G Campus laboratory. This 5MBS prototype is able to deliver multicast content over the N3 interface, and incorporates the new associated procedures between the Multicast Broadcast Session Management Function (MB-SMF) and Multicast Broadcast User Plane Function (MB-UPF) to manage, create and destroy the multicast tunnels. Based on an extension of the commercial software Open5GCore, the multimedia content is streamed from a video server, enters the 5G Core, and then is forwarded to an emulated RAN and devices. The thesis has focused on the bandwidth coursed over the N3mb interface using multicast tunnel. The work done is part of the [R3] project.

1.5 List of Publications

1.5.1 Publications and Activities Related to this Thesis

International Journals

[J1] M. Säily, **C. Barjau**, D. Navratil, A. Prasad, D. Gómez-Barquero and F. Tesema, "5G Radio Access Networks: Enabling Efficient Point-to-Multipoint Transmissions, " *IEEE Vehicular Technology Magazine*, vol. 14, no. 4, pp. 29-37, September 2019.

[J2] M. Säily, **C. Barjau**, J. J. Giménez, F. Tesema, W. Guo, and D. Gómez-Barquero, and D. Mi "5G Radio Access Network Architecture for Terrestrial Broadcast Services," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 404-415, June 2020.

[J3] T. Jokela, J. Kalliovaara, H. Kokkinen, B. Altman, **C. Barjau**, P. Sanders, D. Gómez-Barquero, and J. Paavola "Multimedia Public Warning Alert Trials Using eMBMS Broadcast, Dynamic Spectrum Allocation and Connection Bonding," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 571-578, June 2020.

[J4] T. Tran, D. Navratil, P. Sanders, J. Hart, R. Odarchenko, **C. Barjau**, B. Altman, and D. Gómez-Barquero, "Enabling Multicast and Broadcast in the 5G Core for Converged Fixed and Mobile Networks," *IEEE Communications Letters*, vol. 66, no. 2, pp. 428-439, June 2020.

International Research Visits

[V1] Turku University of Applied Sciences. August - November 2018 (3 months).

Research Projects

[R1] 5G-Xcast: Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems (H2020 No761498).

- Funding institution: The European Comission.
- Start date: 01/06/2017
- Duration: 25 months

[R2] 5G-TOURS: SmarT mObility, media and e-health for toURists and citizenS (H2020 No856950).

- Funding institution: The European Comission.

- Start date: 01/06/2019
- Duration: 37 months

[R3] FUDGE-5G: FUlly DisinteGrated private nEtworks for 5G verticals (H2020 No957242).

- Funding institution: The European Comission.
- Start date: 01/09/2020
- Duration: 30 months

International Conferences

[C1] J. Costa-Requena, **C. Barjau**, S. Borenius, "Transport layer and Synchronization for Smart Grid and Industrial Internet in 5G Networks," *SmartGridComm 2019*, Beijing, China, October 2019.

[C2] **C. Barjau**, M. Säily, D. Gómez-Barquero, "Enabling SFN Transmissions in 5G Cloud-RAN Deployments," *BMSB 2019*, Jeju Island, South Korea, June 2019.

[C3] **C. Barjau**, D. Gómez-Barquero, H.Y Jung, S.I Park, N. Hur, "Limitations of ATSSS technology in ATSC 3.0-5G convergent systems," *BMSB 2021*, Chengu, China, August 2021.

Patents

[P1] H.Y. Jung, S.I. Park, H.M Kim, N.Hur, D. Gómez-Barquero, E. Garro, **C. Barjau**, "Integrated core network of 5g and atsc 3.0, control plane entity and method for transmitting multimedia content in control plane entity," Patent No US20210377318A1, June 2020, **Pending**.

[P2] H.Y. Jung, S.I. Park, H.M Kim, N.Hur, D. Gómez-Barquero, **C. Barjau**, "METHOD FOR INTERCONNECTION BETWEEN ATSC 3.0 AND 5G CORE NETWORK, USING ATSSS AND QUIC CONNECTIONS," January 2022, **Submitted**.

Chapter 2

Pre-Release 17 Mobile Broadcasting

This chapter presents the research efforts performed to provide Mobile Broadcasting before the standardization of 5MBS in Release 17. 3GPP has included the possibility to do multicast and broadcast transmissions since 3G, in a system called Multicast Broadcast Multimedia Services (MBMS). The first iteration of the system was a commercial failure for diverse reasons, including the need for specific terminals and the limited capacity offered by the technology. In future releases, MBMS has received many improvements, with the most notable one being the migration to 4G, in a revised version called eMBMS in Release 9, while keeping backwards compatibility with previous iterations. However, the first versions of 5G did not provide a Point-to-Multipoint (PtM) mode. This chapter aims to highlight this period, between 4G and 5G, in terms of standardized technology, research initiatives and trials, and limitations of the eMBMS solution. It is structured as follows: 2.1 introduces eMBMS, its architecture, and the enhancements experimented during the 4G lifecycle, and two applications, IoT and PWS, which leverage eMBMS to provide new functionalities; 2.2 is a limitation analysis of eMBMS Release 15, which influenced the design of the H2020 European Research Project 5G-Xcast, presented in detail in 2.3.

2.1 eMBMS in Release 14 to 16

The introduction of broadcast capabilities in 4G was mostly focused towards broadcasters initially. But future iterations of the technology split eMBMS towards two different tracks: one more oriented to mobile operators, seeing broadcast as a network optimization technique; and the other track considered broadcast and television delivery as a service itself. Nevertheless, from Release 14 onwards, most of the enhancements of eMBMS were made to make it a viable Terrestrial Broadcast standard, solidifying its position as a broadcast technology. This section covers the fundamentals of eMBMS; the most relevant changes of the Release 14 version known as ENTV, and the enhancements made for the Release 15 and 16 that define the current 5G Broadcast concept.

2.1.1 eMBMS introduction

eMBMS is a full solution and an extension over the LTE EPC and RAN in order to offer broadcast services.The main pillars that compose eMBMS are the new PtM radio bearers and multicast support in the core network; with small changes to the existing radio and core network protocols of LTE. Additionally, it requires additional network entities at RAN and Core, interfaces to connect them, waveforms at Physical Layer, logical and transport channels at RAN; and protocols or procedures to manage, operate, configure and provision broadcast services. In detail, eMBMS architecture can be seen in Figure 2.1, and adds the following entities to the Core Network:

- Multicast Broadcast Multimedia Services Gateway (MBMS-GW). Propagates the incoming data towards the RAN, using multicast over M1 interface. The User Plane functionalities include the management of the multicast tunnels between the eNBs using IGMP. In these tunnels, the involved eNB must join the multicast group in order to receive the broadcast data to be radiated. At the Control Plane, it exchanges signalling for establishing the eMBMS bearer over the SG-mb and Sm interfaces.

- Multicast Coordinator Entity (MCE). This entity controls the Radio Resource Allocation and the decision of the transmission mode used by an eMBMS service, either Multicast Broadcast Single Frequency Network (MBSFN) or Single Cell Point-to-Multipoint (SC-PTM). Additionally, the MCE chooses the Air Interface parameters and commands the eNBs to launch the MBMS transmission, monitoring any error by the eNBs. It is deployed in the RAN, with two different possibilities: A centralized deployment, where a single MCE addresses the control part of several eNBs over the M2 interfaces, or distributed, where each eNB incorporates the MCE functions inside (and the M2 interface is omitted).

- Broadcast Multicast Service Centre (BM-SC). It is the central entity of the eMBMS framework and where most of the intelligence of the framework resides. It is the entry point of the multimedia content into the

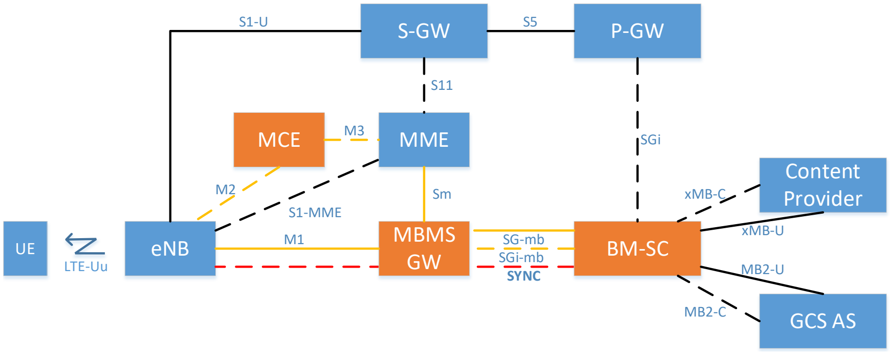


Figure 2.1: eMBMS reference architecture. The baseline architecture of LTE is expanded with the new network elements BM-SC, MBMS-GW and MCE, highlighted in orange. Over the SGi-MB and the M1 interface, the SYNC protocol encapsulates the eMBMS packets, providing TTA and packet numbering in order to perform the SFN operation.

4G transport network, where it schedules, starts, modifies or stops the MBMS service. In other words, the BM-SC performs the management of the eMBMS sessions and bearers. Other notable functionality includes the Session and Transmission Function, where the Temporary Mobile Group Identity (TMGI), an unique identifier, is mapped to MBMS services; and the QoS used for the service is selected. Another vital function of the BM-SC is the Service Announcement, where the BM-SC creates the Service Manifest or the User Service Description (USD), which is needed for devices to discover which services are being radiated and with what video format. This Service Announcement can be precoded into the devices or delivered over a secondary link like Wi-Fi from a-priori known address. Other relevant functions performed by the BM-SC is the forward error correction in the form of Application Layer Forward Error Correction (AL-FEC) Raptor codes [28]. Both Service Announcement and AL-FEC are carried by the File-based Delivery over LTE-based eMBMS (FLUTE) server inside the BM-SC [29], alongside content encryption or transcoding. Lastly, the BM-SC performs synchronization configuration and applies SYNC protocol to the outbound packets. The encapsulated multimedia stream is forwarded to the MBMS-GW.

eMBMS defines a transmission mode named MBSFN. MBSFN creates SFNs, where a group of eNBs are transmitting the same data, with the same radio parameters, at the same time. The main advantages of an SFN are the increased coverage and the stable reception quality across the cell area by turning the destructive interference into a constructive one [30]. However, the waveform must adhere to the SFN requirements: a new type of subframe, MBSFN subframe, is introduced inside the LTE Air Interface alongside a new physical channel, Physical Multicast Channel (PMCH). For these MBSFN subframes, broadcast radio resources must be reserved, ranging from 10% up to 60% resource allocation (before Release 14) of the whole LTE frame. These subframes will then carry PMCH data only, i.e eMBMS data can be multiplexed, thus it is not possible to map unicast data into MBSFN subframes, even if there is no multimedia data available to be broadcasted. Additionally, it is the mandatory addition of unicast control part even in 60% eMBMS allocation schemes, adding overhead to the broadcast transmission. Other changes to the physical layer include longer cyclic prefix and dedicated reference signals for PMCH. New transport and logical channels to support broadcast are introduced at the higher layers of the RAN. The logical channels include the Multicat Control Channel (MCCH) and the Multicast Transport Channel (MTCH). MCCH carries acquisition information for the UE to tune in a certain eMBMS service, as well as all the services available in the cell, and is periodically transmitted in the PMCH. Note that this scheduling period is customizable. The MTCH multiplexes the eMBMS data of one or more services and forwards data to the PMCH. The added transport channel is the Multicast Channel (MCH) which is tasked with scheduling all the services coming from the MTCH according to MME signalling.

As previously said, eMBMS features a synchronization protocol for the radio nodes applied at the BM-SC, named SYNC [31]. The SYNC protocol is designed to ensure the synchronized transfer of MBMS user data from different cells to the UEs in the MBSFN mode. To do so, SYNC provides in its headers the Time To Air (TTA) or timestamp while encapsulating the rest of the payload at the RLC layer. There are several types of SYNC packets, but they can be summarized into Type 0 or heartbeats, without payload; and the rest with different type of headers and payload formats [32]. A typical MBMS delivery between the MBMS-GW and the eNBs will look like periodic Type 0 packets in a row with a single or several interleaved Type 1,2 or 3. To avoid eNB interfering the SFN by radiating incomplete MBMS frames, the SYNC protocol includes the capability to detect corrupted or lost packets in a given time interval, denominated Synchronization Sequence and configurable by the operator. Inside the SYNC header, it is included the packet number and the total octet number of the current Synchronization Sequence. With these two values, the eNB can derive how many packets and data were lost in the Synchronization Sequence. The specification in [31] defines the eNB behaviour when detecting these losses based on configurable thresholds. Shown in Figure

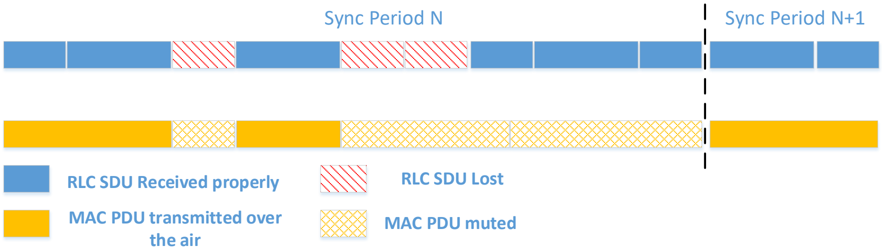


Figure 2.2: SYNC sequence example, where three SYNC packets belonging to the same synchronization sequence are lost.

2.2, when an eNB detects a SYNC encapsulated RLC SDU lost packet, the eNodeB will not radiate the associated MAC PDU to avoid interfering with the rest of the SFN transmitters. In the case that the error persists and more SYNC packets are lost, the eNodeB will stop the transmission until the next Synchronization Sequence begins.

To manage the services, SFN areas, and geographical areas to radiate, eMBMS introduces concepts in order to manage the provision of broadcast services [33]:

- MBMS Service Area. This is the geographic area where the broadcaster or mobile operator wants to provide a service, using MBMS bearers. MBMS Service Area is composed of 1 or more MBSFN areas. Each MBMS Service Area is identified by one or more Service Area Identifier (SAI). These SAIs identify single or group of cells.

- MBSFN Area. A group of synchronized cells forming an SFN. A single cell can belong to several MBSFN areas at the same time. The number of eNBs under the maximum Intersite Distance (ISD) is known as the MBSFN Synchronization Area. MBSFN Synchronization Area marks an upper bound distance where the SFN waveform still interferes constructively i.e. the arrival time of every PMCH signal in a MBSFN Area does not exceed the Guard Interval.

- Reserved Cells. Cells where the operator deliberately chooses to stop the transmission of the MCCH or the PMCH altogether, forbidding new users to tune into the service. These cells are usually located at the edge of the MBSFN area where the QoS cannot be guaranteed, due to neighbour interference. While new users cannot receive the eMBMS transmission, service continuity of already tuned users who handover into the Reserved Cells is maintained since the multimedia is being broadcasted.

In order to tune into broadcast content, the UE must acquire the MBMS user service [34]. MBMS user service can be interpreted as the catalogue of multimedia broadcasts being radiated in an area, and is advertised to UEs using the BM-SC Service Announcement functionality, which provides the information such as parameters required for service activation (e.g. IP multicast addresses, starting time etc.). On the UE side, an application or a middleware, featuring a MBMS client, requests this client to receive a service which is uniquely characterized by a TMGI. In LTE, the UE then searches for the service in cells on frequencies indicated in the USD file or bands indicated in Signal Information Block (SIB)15 for the TMGI. To tune and display the service, the UE has to acquire SIB2, SIB13, MCCH, SIB20 and Single Cell Multicast Control Channel (SC-MCCH) to determine whether the service is being transmitted. MCCH or SC-MCCH and possibly SIBs are updated when MBMS services is started in LTE. UE shall attempt to receive MCCH change notification and SC-MCCH change notification in each modification period. The change notification triggers UEs to reacquire MCCH or SC-MCCH and if the MBMS service of interest is included in the new information on MCCH or SC-MCCH then this is also the trigger for the UE to configure radio bearers for the service and receive the service. Afterwards, the UE will look for the content in the PMCH subframes, decode it and display it to the user.

As many of other 3GPP technologies, eMBMS experienced several enhancements from the Release 9 initial version. Two noteworthy additions are 1)SC-PTM, and 2) Multicast operation on Demand (MooD). SC-PTM [35] is an alternative delivery mode to MBSFN, using a new set of logical channels that are mapped into the Physical Downlink Shared Channel (PDSCH) instead of PMCH, allowing the multiplexing of unicast data with broadcast, but losing the ability to perform SFN. SC-PTM is oriented towards localized groups requiring PtM communications, e.g. firefighters using a push-to-talk application based on eMBMS. On the other hand, MooD-enabled BM-SC is capable to monitor the number of users watching a given service over unicast via Reception Reports, and when a given audience threshold is reached, the BM-SC automatically launches a MBMS session with the consumed content and notifies the MBMS capable users to switch to broadcast. When the demand of the popular content winds down, these users are transferred back to unicast. This technology has been deployed in Australia by Telstra, Enensys and Ericsson [5].

2.1.2 ENTV: eMBMS in Release 14

Broadcasters did not consider the eMBMS iterations before Release 14 as a viable Terrestrial Broadcast technology. They highlighted several shortcomings, for example, that the standard did not allowed for 100% resource utilization of radio resources, or the maximum allowed ISD was not enough for the current HPHT deployment. Release 14 eMBMS was a joint effort between the broadcast industry and 3GPP, working towards overcoming the eMBMS limitations. The outcome of this was a suite of changes to accommodate eMBMS as a candidate technology for Terrestrial Broadcast, known as Enhanced Television Services over 3GPP eMBMS (ENTV) [36]. ENTV was introduced in 2017, and incorporates changes from Core Network to Air Interface and targeting existing broadcast infrastructure. Regarding the Air Interface, changes included new numerologies supporting diverse subcarrier separation and larger distance between transmitters. Additionally, up to 100% resource allocation from an LTE carrier can now be mapped to eMBMS transmissions, while omitting the unicast control part, deriving in reduced overhead and increased capacity. A new type of subframe, called feMBMS subframe, represents this fully allocated broadcast carriers. This new subframe type includes the Cell Adquisition Subframe (CAS) to let terminals tune to the signal quickly. Finally, in case there is no MBMS data available at PMCH, unicast data can now be multiplexed in MBMS subframes. To allowed further ISDs, new Guard Interval parametrization was added (200μs), which provided around 60 km ISD [37].

At the Core Network, the following new features are introduced:

- Receive Only Mode (ROM), in which SIM-less devices can tune in to ENTV transmissions without being registered with the network. This enables free-to-air content to be radiated over LTE infrastructure. A Receive-Only Mode without the need of a SIM can significantly reduce the receiver complexity by omitting the traditional unicast functionality.

- Transport or transparent delivery mode, where the multimedia content from the service provider is just forwarded as it is, without any transcoding. The BM-SC will only apply SYNC to the packets and then forward the multimedia packets coming the Content Delivery Network (CDN) into the MBMS-GW. From a service perspective, the transparent delivery mode facilitates the provision of data encapsulated in traditional broadcast formats, e.g. as MPEG Transport Streams, without transcoding

- A standardized, RESTful interface called xMB to expose BM-SC capabilities to trusted 3rd parties, so sessions can be created remotely. xMB interface offers content providers a simplified access to MBMS core network elements, e.g. for service establishment, monitoring and stop. Alongside this exposure API, ENTV also defined the MBMS-API, which provides tools for developers to program applications with specific function calling between the UE and the BM-SC, abstracting the middle layers and easing the implementation.

- Signalling support for shared broadcast transmissions under one LTE carrier. This allows for several MNOs to connect into common infrastructure and radiate broadcast services over one frequency band; instead of replicating the MBMS services per operator. Network operators can choose to share a feMBMS overlay to provide a common broadcast platform, reducing the total resources needed to distribute popular services.

To summarize, ENTV brought several innovations that turned the eMBMS technology into a potential candidate for Terrestrial Broadcast deployments. These changes, while not finished, will be the foundation of the upcoming 5G Broadcast.

2.1.3 5G Broadcast: eMBMS in Release 15 and 16

3GPP drafted their requirements for the 5G technology [38]; with sections allocated to multicast/broadcast capabilities. An SI [39] evaluated if the ENTV version of eMBMS did fulfil those requirements, identified those which were not, and suggested improvements to eMBMS in order to overcome the requirements. Note that, in the case that eMBMS ENTV or future versions satisfy these requirements, it would be considered a 5G technology that uses LTE and without using any 5GS specific components. The requirements in question are:

- 1) The Radio Access Technology shall support existing broadcast services and accommodate new ones.
- 2) The Radio Access Technology shall support the dynamic adjustment of the broadcast area, based on different metrics, such as service specific requirements or user geographical distribution.
- 3) The Radio Access Technology shall support the concurrent delivery of broadcast and unicast data.
- 4) The Radio Access Technology shall support multiplexing of user data in time and frequency domains.
- 5) The Radio Access Technology shall support static and dynamic resource allocation between unicast and broadcast, up to 100% broadcast resources allocated.
- 6) The Radio Access Technology shall support broadcast network sharing between several MNOs.

- 7) The Radio Access Technology shall support large SFN geographical areas, up to 100 km radius.
- 8) The Radio Access Technology shall support UE mobility up to 250km/h.
- 9) The Radio Access Technology shall support multiple antennas RAN equipment to increase capacity.
- 10) The Radio Access Technology shall support Multicast/Broadcast services for machine-type communications.

As an outcome of the Study Item, the 3GPP participants concluded that only two of the aforementioned list of requirements were not fulfilled while another two of them were fulfilled partially. The rest are already satisfied in eMBMS Release 14. In particular, requirement 5 or the dynamic resource allocation is considered partially completed since allocations ranging from 60% to 80% force the eNB to become a secondary cell. Regarding requirement 9, limited precoding schemes and diversity gains can be obtained by using multiple antennas, however, nor MBSFN or SC-PTM support the full MIMO operation mode. For the non met requirements, requirement 7, the SFN areas radius, it is limited by the Guard Interval duration. It was proposed to allow for even longer durations, from the 200μs of Release 14 into a new 300μs in Release 16. Similarly, for requirement 8, a new Subcarrier Spacing of 2.5 KHz is introduced in Release 16, which can provide mobility up to 250km/h.

These enhancements, alongside the aforementioned ENTV ones of Release 14; constitute what is known as **5G Broadcast**. It is a Terrestrial Broadcast standard which fulfils the 5G requirements, can address mobile and roof-top antennas, has interoperability with mobile and broadcaster infrastructure, and device support [40]. Several trials have been carried during 2022 featuring specific parts of 5G Broadcast, including a retransmission of the 2022 Eurovision contest [41] and Roland Garros tournament coverage [42].

2.1.4 Applications of eMBMS beyond multimedia delivery

The benefits to point-to-multipoint transmissions are not only limited to Linear TV. Other verticals, such as V2X, IoT and PWS can also benefit from the scalability, radio synchronization, coverage, improved reliability and reduced latency that PtM provides. Two applications designed in the context of the thesis are listed next, one which provides a synchronization system in Industrial environments for IoT; and the other uses an eMBMS transmission to alert devices of a disaster, acting as a PWS solution.

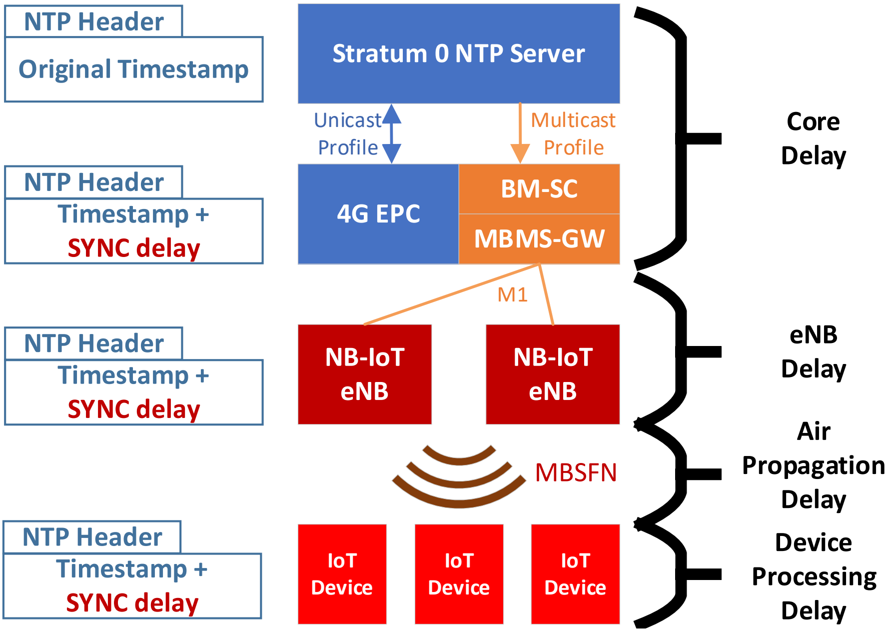


Figure 2.3: Synchronization model for IoT devices in a factory floor, delivered over eMBMS. Since SYNC is mandatory for eMBMS transmissions, the eNBs radiate the broadcast subframes synchronously, which is used to carry NTP packets, allowing IoT devices to acquire the factory clock timing.

eMBMS as an IoT Synchronization System

In [43] a synchronization system for IoT devices in a factory is proposed, based on Network Time Protocol (NTP) multicast profile mode and eMBMS. While the use for eMBMS in IoT is already standardized [44] but only covered the use of broadcast to provide software updates to a massive number of users. The proposed system relies on the fact that eNBs belonging to a MBSFN are intrinsically synchronized thanks to the mandatory SYNC protocol. The synchronization deliver system uses eMBMS to broadcast adjusted downlink timing information periodically to each IoT device to synchronize their internal clocks to a common source or correct any timing deviations. ENTV transmission method Transparent Delivery is used to carry a modified version of NTP packets to all wireless devices located in a factory floor.

The proposed method to reach high accuracy in wireless connected industrial devices consist of using a periodic eMBMS subframe in a NB-IoT transmission. The wireless system as shown in 2.3, is composed by an NTP Broadcast

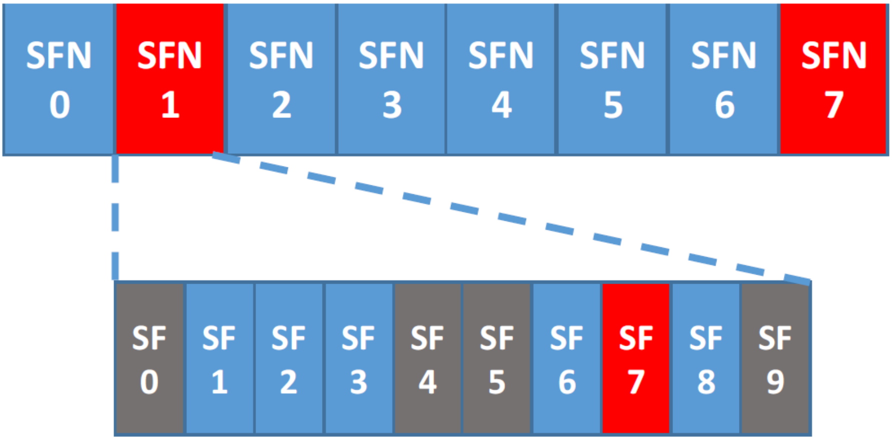


Figure 2.4: Frame structure showing System Frame Numbers (in blue) with embedded MBSFN subframes (in red). In this example, radioframeAllocationOffset is 1, radioframeAllocationPeriod is 6 and subframeAllocation is 000010.

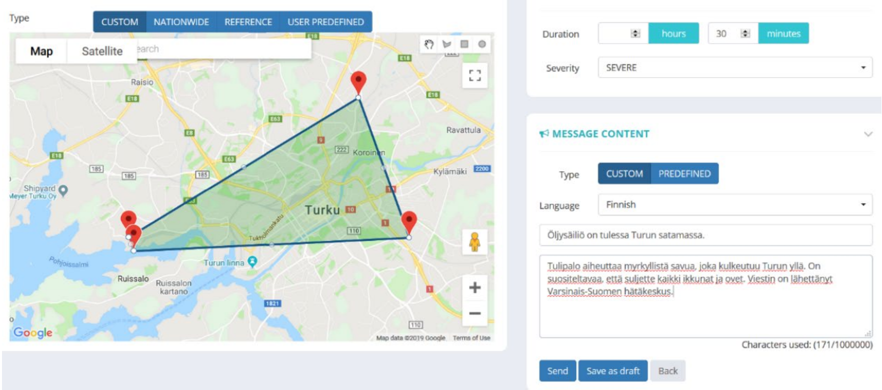
Mode server, one BM-SC alongside a MBMS-GW with Transparent Delivery Mode functionalities, one NB-IoT capable MCE, several eNB with MBSFN plus NB-IoT, and an arbitrary number of IoT devices. A stratum 0 timing source (e.g. from GPS signal) provides either NTP, operating in broadcast mode. These packets are used as a payload for the eMBMS session. Moving to the BM-SC, the source packets (usually multimedia data, but in this solution, NTP timing packets) are forwarded to the MBMS-GW without any re-encoding. SYNC protocol encapsulates the NTP packets, adding packet sequence numbering and TTA headers. The RAN is formed by one or several eNB, depending on the deployment chosen. Each eNB incorporates the Multicast Coordination Entity or MCE, a logical entity part of the eMBMS architecture, forming a distributed MCE deployment. The MCE role is to choose the radio parameters of the MBSFN based on the QoS Class Identifier mapped to each multicast flow, and this decision must be consistent across all eNB in order to fulfil the MBSFN requirements. Note that not all NB-IoT radio resources are needed to be allocated to eMBMS. In fact, NTP requires very little bandwidth to carry each multicast packet. The resource allocation of the radio frames dedicated to MBSFN can be found in the SIB2, where 3 parameters configure the allocation of the MBSFN subframes: radioframeAllocationPeriod, radioframeAllocationOffset and subframeAllocation. An example of this frame structure can be seen in Figure 2.4.

The first parameter defines the interval between frames until a new MBSFN subframe is allocated, the second parameter indicates the starting frame relative to the System Frame Number 0, and the third parameter indicates which subframe inside the frame is the one carrying multicast data. Given existing value ranges of these parameters, the maximum period of multicast timing transmission is 1 MBSFN subframe every 32 NB-IoT frames. Choosing these values provide the least bandwidth consumption used for timing delivery, which is a very scarce resource in NB-IoT systems. Target receivers are IoT devices, which capabilities range from simple sensors to complex precise equipment like production machinery, video surveillance and many other several applications. For this timing proposal system to work, all of the IoT devices must incorporate eMBMS capabilities. Low-end, simple devices restrained by memory and processing capabilities can make use of the multicast NTP to correct their internal clocks. High-end, precise devices can obtain PTP sync packets from other point-to-point sources like 5GTSN, and feed them to the dedicated PTP hardware in order to obtain more accurate timing information than the NTP multicast provides. Overall, the delay experimented by the source NTP packets until they reach the IoT devices can be divided in: Core Network delay, eNB delay, Air Propagation delay and Receiver Processing delay. Core Network delay contains the transmission delay from the NTP source server and the NTP packet processing inside the BM-SC. eNB delay comprises the transmission delay from the MBMS-GW, the required buffering time of the SYNC protocol and any internal processing time required by the eNB. Air Propagation delay is the time taken by the radiated timing packets by the eNB to reach the IoT device. Finally, the Receiver Processing time is totally dependent on the device capabilities, alongside the time required to undo the eMBMS Physical Layer and deliver the packet to the device higher layers. However, the use of SYNC protocol at the BM-SC can turn the Core and eNB delay into a deterministic delay. Since SYNC forces the eNB to put into air determined eMBMS packets, the overall delay from the NTP source server and the packets are radiated is contained inside the SYNC TTA headers. By adding the SYNC delay to the NTP timestamps as they cross the BM-SC, Core and eNB delay can be compensated. For the Air Propagation delay, the Timing Advancement procedure at Uplink used in LTE and NR can be exploited. When a terminal attach to the network using the RACH (Random Access Channel), the eNB evaluates the arrival time to the frame timing and tells the device to advance their transmission by an amount specified in the Timing Advancement Control Elements to avoid interference with other users. For example, in LTE, this value is a 16 times multiple of the basic time unit Ts (0,0325 Î¼s) which provides a maximum timing range of $1282 * 16 * Ts = 666.64\mu s$. If the IoT device operating system has access to the Timing Advancement signalling used by the RF modem, the Air Propagation delay can be corrected by the upper layers. Finally, the Receiver Processing time, unless specific hardware is used for the timing correction, can be considered random.

In summary, Core and eNB delay are compensated by SYNC, Air Propagation delay is compensated by eNB Timing Advancement messages, and Device Processing delay is random and thus, a source of error in timing measurements.

eMBMS as a Public Warning System

The main motivation of using a modern broadcast solution in PWS comes from the limitations in the existing ones. The most widespread solution nowadays is Cell Broadcast [45], which is deployed in many countries including Japan, China, United States, Canada, and more [46]. However, this technology, while scalable and good coverage area, has limitations. For example, as the content is based on SMS, is limited to text only alerts. A more capable system, that can deliver multimedia content beyond text, could improve the readability of the alert, provide visual instructions (e.g. go to a close shelter), include more languages, including sign language... In this regard, it is proposed that eMBMS can provide this functionality, where the system provides several text and multimedia files bundled together and it is a smartphone app the one which will decode the files and present them to the user. To showcase this, a PWS trial done in Turku, Finland; during 2019, and documented in [47], as part of the 5G-Xcast project. The trials performed simulated three different scenarios: an amber alert, notifying of a missing child, alongside a photo of the child; a flooding scenario where the eMBMS alert carried a map to the closest shelter; and a oil tank fire in the port, engulfing the city with a toxic cloud, sending the users a map of the affected areas. Technology wise, Cell Broadcast was used alongside the eMBMS transmission. In the limitation section of 2.2 was noted how the paging of users to start receiving eMBMS transmissions was a limitation; since it was not feasible for users to constantly monitor eMBMS messages waiting for natural disasters to happen. To overcome this limitation, Cell Broadcast is used to notify a large group of users that an alarm is occurring, and further info can be found on a link included in the message. Clicking this link will open a smartphone application (in this trial, it is Android based), which interacts with the eMBMS Middleware, to start the eMBMS reception and receive the full information of the alert, sent in carousel over the duration of the trial, in the form of additional files alongside the original Cell Broadcast text. To not overwhelm the users, the Cell Broadcast alert can be configured to be sent periodically. A web application was developed by the project consortium, in which the operator is able to define a geographical area, the text



Duration 30 hours minutes

Severity SEVERE

Language Finnish

Öljysäiliö on tulessa Turun satamassa.

Tulipalo aiheuttaa myrkyllistä savua, joka kulkeutuu Turun yllä. On suositeltavaa, että suljette kaikki ikkunat ja ovet. Viestin on lähettänyt Varsinais-Suomen hätäkeskus.

Characters used: (171/1000000)

Figure 2.5: The PWS application used for the 5G-Xcast trials. Extracted from [47]

message and the additional files to be broadcasted with the message as shown in Figure 2.5.

For the actual experiment, instead of using Cell Broadcast to page the users into the eMBMS transmission, the Google Firebase Cloud Messaging service was used. The behaviour is similar, where the smartphone app would receive the notification instead of the low level RF functionalities of the phone chipset. The component used to deliver the paging data is included as part of the PWS BM-SC. The initial paging alert, when triggered, ranged from 10 to 60 seconds to be received in each phone of the experiment, depending if the context was already setup in the Core Network. Regarding the particular BM-SC parametrization used in the trials, it was chosen a bitrate of 700 Kb, encoded with Raptor FEC 10 which provided protection up to 25%, and using a defined QoS Class Identifier (QCI) of 2 to differentiate the service in the commercial RAN nodes from unicast ones. In the RAN, for the MCCH and the MTCH the same parameters were chosen, using 18 and 9 as MCS values for the test. 10% of the overall unicast subframe was allocated for eMBMS. One important note is that the configuration of SYNC parameters both at RAN and the BM-SC is important, choosing the same time reference at both sides. As explained earlier, if the parameters are not matched, the eNB will drop the entire frame as defined in the SYNC protocol. The signal quality was managed by the application of attenuators at the output of the eNB. The findings in the trial found a correlation between the attenuation applied, the number of packet lost and the time that the devices took to download the packet. As the attenuation was increased, the average time to receive packets increased as well, so did the packet losses over the air interface. It was also tested to lower the

MCS, making the signal more robust. In these high attenuation environments, the eMBMS alert could be still be received within a reasonable time. More details about the experiments themselves and the results are summarized in Table I of [47].

2.2 eMBMS limitations

eMBMS inherited many concepts and ideas from its 3G version, MBMS. This first version was initially designed as a solution for broadcasters to provide linear TV services over cellular infrastructure, but the first versions of the technology were quite limited in terms of area configuration, session management features and application management. Most of the limitations originate from the backwards compatibility philosophy followed by 3GPP, where future iterations of a feature must be compatible with older ones. The limitations were studied in [48] and had impact in the design of the 5G-Xcast solution, detailed in 2.3. They are summarized in next sections, alongside the proposed changes to overcome the limitations.

2.2.1 Static configuration of MBSFN

MBMS Service Area and MBSFN Area are statically preconfigured before MBMS bearers are launched. The cells belonging to MBSFN Areas must be configured before it is possible to launch an MBMS bearer. I While there are mechanisms that allow the BM-SC to modify the list of MBMS Service Areas for an on-going MBMS service, the MBMS Service Areas and cells that form them are statically configured by the MNO and are not adaptive to user demand. This mainly affects MooD functionality; where the seamless switch between unicast and MBMS data bearer is done per MBMS Service Area and does not adapt to the actual geographical location of the users. Depending on the static configuration of MBMS Service Area, the unicast-to-multicast traffic offloading may initially occur in a MBMS Service Area covering a wide range of cells where the demand may only come from one cell. Either a 1:1 mapping of SAI to a cell or the use of the cell list introduced as part of SC-PTM is needed to start an MBMS session without overextending the MBMS transmission. Currently SAI assignment to cells is achieved through OAM configuration and there is no standardized way to dynamically allocate SAI to MBMS Service Area based on traffic demand. Allowing dynamic SAI allocation can improve the efficiency of MooD. In addition, within the same MBMS session, there is no available procedure to quickly switch between SC-PTM and MBSFN delivery mode based on user traffic without relaunching the MBMS bearer. Relaunching the MBMS bearer could cause interruption of the service and force the UE to reconnect to the new MBMS session. Since the air interface channels used for SC-PTM and MBSFN are different, extending SC-PTM over one cell to form a MBSFN Area is impossible, without relaunching the MBMS Bearer to change the delivery mode to MBSFN. Even if this procedure is manually performed by OAM, there are no specified protocol to inform the UE of this change. MooD is not able to switch between SC-PTM and MBSFN, even if one mode is more optimal for media delivery over the other in a certain scenario. An ideal system should switch between unicast, to Single Cell point-to-multipoint, up to a dynamically created MBSFN Area, based on user demand, and vice versa.

Related to this, a distributed MCE deployment where each eNodeB has the MCE functionality incorporated, forming a MBSFN area, needs direct intervention of OAM to ensure that the operation of each involved MCE is coordinated. An OAM interface with every MCE/eNodeB is needed to ensure the MBSFN area configuration is the same across all cells and MCEs/eNodeBs. This interface is implementation specific to a network vendor which makes multi-vendor deployment of larger MBSFN areas more challenging for operators. The use of a standard interface to normalize the signalling between OAM and the MCEs would improve the interoperability and management of large MBSFN areas. Also, when the BM-SC establishes an MBMS session with the desired QoS, every MCE/eNodeB forming the MBSFN Area, which receives the MBMS session start request message, must configure the exact same RAN parameters of MBSFN area i.e. MCCH and MTCH, to enable the SFN. The MNO must consider the implications of a coordinated configuration of air interface parameters for every eNodeB in the MBSFN Area, especially if there is a diverse set of eNodeB hardware and software used on the eNodeBs forming the SFN with its own MCE implementation. Additionally, the structure of MCCH and MTCH with the corresponding procedures such as MCCH update were driven by the design of underlying physical layer frame structure for MBSFN that relies on the semi-static segregation of MBSFN resources from unicast resources. The RRC signalling and the use of system information signalling of MBMS configuration inherit the semi-static nature of MBSFN. Altogether, MBSFN transmission is not suitable for dynamic scheduling.

SAI has been previously mentioned. It is an identifier that references a single or a group of cells, with the possible value ranging from 0 to 65535. This puts an upper bound to the number of cells addressable by a 1:1 SAI to cell mapping. The number of cells in the network may be significantly larger than the maximum number of 65535. While nation-wide MBMS can be enabled using the special value '0', it is still not practical to achieve this in case of MNO sharing infrastructure or when specific service e.g. PWS requires fast setup of region-wide MBMS across different MNOs. Another issue with 1:1

SAI to cell mapping is the possible loss of advantage of MBSFN delivery mode due to MBMS Service Area containing a single cell. In that case, SC-PTM delivery mode is seen as more appropriate. However, there is an interest to map each SAI value to an individual cell, in order to have access to eMBMS transmission with cell granularity. LTE addressed the issue by using cell IDs or ECGIs along with MBMS SAI to provide cell granularity of the MBMS service area. The issue is that BM-SC still must know the correct MBMS SAI because MBMS SAIs are used to route the control messages towards downstream nodes all the way up to MCE, which then uses the cell IDs to configure the broadcast areas. This two-layer approach increases system complexity and OAM effort.

2.2.2 Lack of feedback on eMBMS session management

The current eMBMS session management procedures are used to start, stop or modify eMBMS sessions. The current eMBMS session management faces the following challenges:

- When an eMBMS session is requested by a BM-SC, the BM-SC has no knowledge if the session has actually started in each eNodeB.
- During an ongoing eMBMS session, the BM-SC has no knowledge if an eMBMS session is pre-empted (terminated) in an eNodeB.

It is possible for eMBMS sessions to fail in the eNodeB due to various reasons such as insufficient capacity, configuration error, software or hardware fault, connectivity problem, or a pre-emption vulnerable bearer due to priority traffic allocation. In detail, to start an eMBMS session, the BM-SC performs the MBMS Session Start procedure. In response to the request from BM-SC, the MBMS-GW sends the answer command with a start or stop indication. The MBMS-GW may not need to wait for a response from the network but it sends the Session Start Response to the BM-SC based on the success of its own local operation related to the MBMS session start procedure, i.e. context creation and user plane allocation at MBMS-GW. There is no procedure to update the BM-SC as result of changes in eMBMS sessions running in the network, for example MBMS session pre-emption. In addition, there is also no message defined between the MBMS-GW and the BM-SC to support this function.

This limitation also exists between the MME and the MBMS-GW over the Sm interface; and the M3 interface connecting the MME and the MCE. Regarding the Sm interface, the message ”Session Start Response” sent in the start procedure gives the impression that the MME is capable of providing feedback to the MBMS-GW, but analysing the Information Element sent, there is only a single Cause field, even though the MME is likely to address multiple eNodeB/MCE for a single eMBMS session. Hence, there is currently no possibility to provide detailed information on which eNodeB a session started or failed using this interface. This situations derives in states where one eNodeB has successfully started a session but every other eNodeB involved in the broadcast transmission would fail, yet the message reported back would be a "success". Additionally, there is currently no procedure or message for the MME to update the MBMS-GW with updated information on on-going eMBMS sessions, for example MBMS session unexpectedly pre-empted. For the M3 interface, in case that the deployment model used is the centralized MCE one, the same limitation arises. The response of the MBMS Session Start can only have one Cause code, which is unable to signal which eNodeB did actually fail. This also limits the MCE to provide information on what method (SC-PTM or MBSFN) was chosen for the transmission to other nodes which may be relevant in scenarios when UE does not support both transmission modes. No message has been defined for the MCE to report any issues with an eMBMS session after it has started.

The application layer of eMBMS is directly affected by this limitation. An application requires an eMBMS bearer to be established in the network to deliver the relevant content. To establish a bearer, the application requests the necessary resources using session management procedures through the BM-SC, over MB2-C or xMB. The application is required to provide the location where the bearer will be needed. This is done by providing the Service Area using a list of SAIs or a Cell Identities list (CI). As the BM-SC currently cannot provide feedback to the application in case the bearer is not started in one or more eNodeBs, the application does not know in which location the resulting service succeeds or fails. Derived from this, enforcing SLAs between content providers and MNOs since success or failure is limited; as the eMBMS signalling framework is inaccurate in reporting on-going statistics.

2.2.3 Lack of feedback from RAN to Core

When the BM-SC wants to activate an MBMS session, a Session Start Request message is sent through the MBMS-GW, the MME to the MCE. If an MBMS Cell List is provided the MCE then decides on whether to use MBSFN or SC-PTM as MBMS delivery mode according to [33]. However, the specification does not provide a guideline for the MCE to make an appropriate selection; this is left to manufacturer implementation. On top of this, the decision is never sent back to the Core Network, causing unwanted radio modes to be selected or waste of radio resources. Another issue related to the cohesive MBMS operation comes from the UE capability which indicates the supported delivery modes. It is desirable for the UE to send its MBMS capability information to the network so that the network store the MBMS capability from all UEs. In addition, eMBMS allows the UE to report on receiving MBMS packets using reception reports but this method does have its limitations: These reception reports are not in real-time and it is difficult to associate a reception report of an error with the true cause of it.

The multi-cell MBSFN transmission in eMBMS is not well suited for services whose QoS requirements vary over time (e.g. variable throughput and best-effort services). When the traffic characteristics of a service change, the content provider is responsible for requesting an update on MBMS session parameters. But the MCE, which controls the MCCH service scheduling, resides in the control plane of eMBMS architecture. Hence, the MCE is not aware of the user plane traffic characteristics. The MCE determines MCCH scheduling information and possibly other configuration based on the information received either in MBMS session management messages over M3 interface or in MBMS overload information from the eNodeB. Both the information received in MBMS session management messages over M3 interface or the MBMS overload notification are insufficient in addressing the architectural drawback and allowing dynamic scheduling of multi-cell transmission.

The SYNC protocol, used to detect errors and provide TTA in the eNodeB for MBMS sessions, has no procedure to indicate lost packets back to the BM-SC. This packet loss detected at the eNodeB can happen anywhere between the BM-SC and the eNodeB. Having feedback on packet loss may help the BM-SC to monitor, troubleshoot if any major problems occur. From UE perspective, it cannot know where the loss is originating from (radio interface or connection between BM-SC and eNodeB), Reception Reports cannot help to indicate the root cause. The lack of actions by the BM-SC may be explained by the fact that when the retransmitted packets arrive at the eNodeB, these packets may be outdated due to the duration of the synchronization sequence, especially when the loss is detected at the end of the synchronization sequence. Trying to retransmit one of those packets is not viable since they take at least one Return Trip Time (RTT) and end up in another out of sequence error. SYNC TTA value should take into account a latency analysis; including the transit and processing time at the MBMS-GW. SC-PTM does not need SYNC protocol since this delivery mode does not require the coordination between multiple cells. At the writing time of this deliverable, 3GPP decide to keep SYNC for SC-PTM.

2.2.4 Trigger eMBMS reception

In eMBMS, the initiative to consume broadcast content relies on the UE. The UE has to become aware that the content of interest is going to be broadcasted or is being broadcasted and then takes the initiative to start up the application that shall fetch and display that content. While this model is suitable for verticals like Linear TV, in case of multimedia Public Warning (PW) messages, an user is not aware when warning messages are broadcasted, because PW messages are not scheduled in advance, they are unexpected by nature. In order to receive a PW message once it is broadcasted, the modem has to continuously monitor MCCH and SC-MCCH control channels change notification, update the internal context, and search for the TMGI associated with PW Service within the new information. But these modification periods are common to all broadcast services under a cell, so when multiple services with diverse latency requirements are provided in the cell, the MCCH and SC-MCCH modification period configuration is driven by the most constrained requirement. This causes UE interested only in services with less constrained requirement to constantly scan MCCH or SC-MCCH for PW broadcasts, deriving in unnecessary battery consumption. This may be a significant issue for a PW message that is hopefully never broadcast.

Another shortcoming is that a TMGI value for PW is currently not standardized. If roaming of PW service is to be supported then the UE must be configured with MBMS service description for any network it can roam in or, alternatively, the MBMS service description could provide a list of alternative TMGIs if other parameters of the service are the same. In both cases, PW service requires international coordination of MBMS configuration between MNOs. To potentially solve the issue, the TMGI for PW services could be the same in all networks both national and international roaming would be supported.

2.2.5 Improvement proposal

This section addresses possible improvement proposals in eMBMS for the LTE version. Some of these limitations cannot be solved without drastic changes to the eMBMS architecture, and instead have been included in the 5G-Xcast architectural design, such as the static and lack of granularity of MBSFN areas, solved by the incorporation of the CU-DU separation of the 5G gNB into the overall point-to-multipoint service provision and described in 2.3. Regarding other limitations, they are listed next which ones can be addressed within the current specification.

Regarding possible improvements to the MME, the session control messages are sent by the MBMS-GW to the MME over the Sm reference point and M3 is the reference point for the session control messages between MME and MCE. The MME is tasked to translate the MBMS Service Area, containing SAI values, into a MBMS Cell List. Then the MME forwards this data to the relevant MCEs involved in the broadcast transmission. However, the BM-SC does not have a way to gather this info from signalling and must be informed of which MCE form the Service Areas by OAM. This can be avoided if the M3 reference point didn't terminate on the MME but instead on the MBMS-GW. The MBMS-GW could then forward the Service Area list to the BM-SC in a standardized way, or alternatively, store the Service Area list in a Network Repository which is accessible by the BM-SC; reducing the dependency with legacy LTE elements for eMBMS.

Concerning the RESTful xMB interface; it currently provides for ”pull” and ”push” HTTP notification procedures. The ”pull” notification is used if and when the content provider wishes to acquire information. Using the ”push” notification, the content provider can indicate its interest in receiving notifications from the BM-SC which then can post the notification to the content provider. Following notification types or levels are supported: Critical, Warning, Information and Session/Service. The improvement lies in the Service/Session notification type, where richer information can be sent from the BM-SC to the application. The Session/Service notification level could be used to deliver information that an MBMS bearer has been pre-empted at one or more eNodeB if it is extended with some new properties which would solve part of the lack of feedback problem. On the other hand, it was presented before that SYNC does not report back any packet losses. To solve the issue, a feedback message for every SYNC sequence whether there are packet losses could be sent from all the eNodeBs within a MBSFN Area. It is then left to the BM-SC to have appropriate action depending on the situation, taking into account the RTT times and the synchronization sequence timers.

2.3 5G-Xcast

5G-Xcast [49] was a H2020 Research project that ran from June 2017 until July 2019. The project had three main goals: 1) To evaluate and provide a 5G-based solution including innovations for the Air Interface, RAN, Core and Application Layer for Broadcast/Multicast services; 2) To find and analyse Use Cases and new business models that can leverage the Broadcast/Multicast capabilities; 3) and to evaluate the performance of the 5G RAT against IMT-2020 requirements [50]. The motivation of the project came from the realization that the first iterations of the 5GS did not include Broadcast/Multicast capabilities, even if they were considered to be a requirement of the technology [51][38]. This is because 3GPP was time-constrained to push NR in time for the IMT-2020 evaluation, and some participants argued that the LTE-based eMBMS framework with the ENTV features could cover all the necessities for Broadcast services in the 5G era. 5G-Xcast project took a blank slate approach, where a Broadcast/Multicast solution was designed from zero. The project produced several deliverables, scientific publications, tutorials and white papers for Broadcast/Multicast services in 5G. In the context of the project, the author work was involved in the identification of limitations in eMBMS, the design of the Broadcast/Multicast Core Architecture and new RAN functionalities to accommodate the possible SFN topologies, specially in Terrestrial Broadcast. A new synchronization scheme, based on an iteration of eMBMS SYNC, was also done by the author as part of the project. Lastly, the author was involved in the calibration of the eMBMS Core and Radio equipment used in the PWS trials. Aforementioned efforts were contributed to the project deliverables, listed below, and several scientific publications.

The 5G-Xcast project carried out trials [52] featuring innovations such as Hybrid Broadcasting, Object-based Broadcasting and Broadcast of Public Warning Services [47]. In the Application Layer, deliverables D5.2 and D5.3 contain the key technologies and the Service Layer intelligence required to fully use the Broadcast/Multicast capabilities of the transport. Regarding the Core aspects, D4.1 [53] describe the proposed architectures to provision Broadcast/Multicast capabilities, while D4.2 [54] extends the previous solutions to converge both fixed broadband and wireless broadband, with all the protocols, signalling and call-flows detailed in D4.3 [55]. The Core architecture will be explained in detail in upcoming sections. Moving into the RAN, an State-of-the-Art evaluation of ENTV eMBMS, compared against other Broadcast standards is done in D3.1 [56]. D3.2 [57] tackles the new NR Air Interface and shows its performance in simulations; while D3.3 [58] and D3.4 [59] are focused on the RAN aspects and RRM and upper layer aspects. RAN architecture has a subsection allocated to clarify its specifics. Lastly, the planning, development, integration and execution of the trials is presented in D6.3 [60] while the final results obtained are reflected in D6.4 [61]. The rest of the section is structured as follows: The 5G-Xcast Core architecture and its two variants is presented, including the design goals, proposed NFs, interfaces, and features of the system. Then, a similar exercise is done for the RAN architecture. Lastly, the last part is dedicated to explain the PWS trials performed as part of 5G-Xcast as an example of the use of eMBMS in new verticals.

2.3.1 5G-Xcast Core architecture

The Core architecture of 5G-Xcast followed the same guidelines and design principles as the Release 15 5G Core [53]. The solution is built on the premise that the Control and User parts of the systems should be separated, modularized as much as possible while being interconnected with well-defined interfaces. This would allow for flexible deployments, where the Control Plane of the 5G-Xcast solution can be instantiated in diverse environments, ranging from deployment over discrete systems, to fully cloud based provisioning. The system also devised with support for SBA deployments, where stateless NFs interact with each other by subscribing or exposing their services using HTTP/2 requests. 5G-Xcast Core was also made Access Network agnostic, where different type of networks could be addressed, so it is not only limited to 3GPP based networks. The additional Broadcast/Multicast capabilities built on top of this paradigm follow additional guidelines: to reduce as much as possible the footprint of the existing Release 15 5G Core, by reusing the 3GPP 5G unicast solution; to consider point-to-multipoint capabilities as a network optimization tool (i.e Broadcast/Multicast as a Transport Network technology), separating the Service Layer aspects from the Core; in this regard, Terrestrial Broadcast is a service over the top that leverages 5G-Xcast technology for devices without uplink capabilities. Last, the setting up of sessions should be as simple as possible, and all the complexity or intelligence is moved into the Service Layer. The 5G-Xcast Core architecture features three main innovations: Seamless multicast switching, incorporation of multilink capabilities, and multi-access edge computing for cache content provisioning. Regarding the seamless multicast switching, it is a novelty based on the same idea as the 3GPP standardized MooD; where depending on the customers consuming reports, the core decides to switch from a point-to-point bearer into a point-to-multipoint one. In the same vein, 5G-Xcast MooD is a series of procedures [62], both at RAN and Core, that chooses the best way to deliver content, be it unicast, multicast or broadcast. Summarized, there are two stages to it: adapting the content to be multicast-capable (e.g. consider which parts of a data session are eligible to be multicasted) and secondly evaluate the best way to deliver this multicast content, be it localized point-to-multipoint at RAN only or both from Core and RAN.

The 5G-Xcast Core aimed to provide both a robust multicast optimization tool, similar to the one existing LTE solutions for Mission Critical services, and the transparent delivery mode introduced in eMBMS Release 14; while designing a framework for point-to-multipoint services that feature data transcoding and reliable delivery (e.g. AL-FEC insertion), the ability to choose with geographical area to broadcast a given service with cell granularity, flexible audience metric gathering and offloading capabilities. To do so, two new NFs were introduced into the solutions: the Xcast User Function (XUF) and the Xcast Control Function (XCF). The XUF supports the user part of xMB interface, and it is intended to be the ingress point for the content into the 5G-Xcast Core. It also features the management of the IP multicast tunnels, the application of AL-FEC or FLUTE capabilities to ensure the correct delivery of files. On the other hand, the XCF supports the control part of the xMB interface, exposing its capabilities and allowing trusted 3rd parties to instantiate broadcast or multicast sessions. Additionally, the XCF is tasked for the resource management of point-to-multipoint services with regards to the other Core NFs e.g. resource allocation in SMF or AMF. It is also expected that the XCF provides the multicast IP address that will be used as ingress point for the UE and the XUF. Service related aspects are also carried by the XCF, like the creation of the service announcement, parsing of the audience reports, AL-FEC and file repair procedures and to execute the switching from unicast to multicast (or vice-versa) based on user reports. The project also proposed two different alternatives for deployment, one more disruptive when compared to the eMBMS one; and the other being more eMBMS-like, easing the possible migration. They are detailed next. Common to both solutions is the addition of two new interfaces: Nxcf and Nx. Nxcf exposes the XCF capabilities to the rest of the other SBA NFs, while allowing the XCF to monitor the status of the Broadcast/Multicast flows by communicating with the SMF and AMF. Nx is used to deliver Broadcast/Multicast specific configuration messages, e.g. AL-FEC parametrization, session announcement manifestos... For further reading, call-flows for both architectures session setup, seamless switching and other procedures are detailed in [55].

The first one shown in Figure 2.6 is characterized by the XUF being connected via N6 to the UPF, behaving like a public network host. In this architecture, the UPF is expected to implement multicast tunnelling technologies like IGMP, Multicast Listener Discovery (MLD) [63] or Protocol Independent Multicast (PIM) [64]; to deliver the Broadcast/Multicast content into the RAN, and to receive this content from the XUF in the N6 interface. This architecture separates the Broadcast/Multicast capabilities from the unicast ones, as the unicast data flows are not affected nor routed through the XUF unless the XCF decides to do a seamless switch to multicast. In that case, the data would get need to get rerouted automatically into the XUF, which will apply or not the FLUTE and AL-FEC functionalities and then deliver it into the UPF. The main delivery mode targeted by this architecture is the transparent multicast delivery, where the users would not know that their content has switched to multicast since they still receive it from the same unicast UPF. Note that the architecture also allows for the CDN to provide multicast content directly into the UPF bypassing the XUF in case some User Plane functionalities are not desired. This architecture proposal is not well suited for SFNs deployments, as the XUF cannot effectively apply SYNC protocol over the N6 interface. But as explained in the next subsection, this synchronization can be performed at RAN directly, if a Cloud-RAN type of deployment is followed. Overall, this architecture provides a very low imprint over the unicast baseline core, easing the adoption of 5G-Xcast solution into existing 5G Cores.

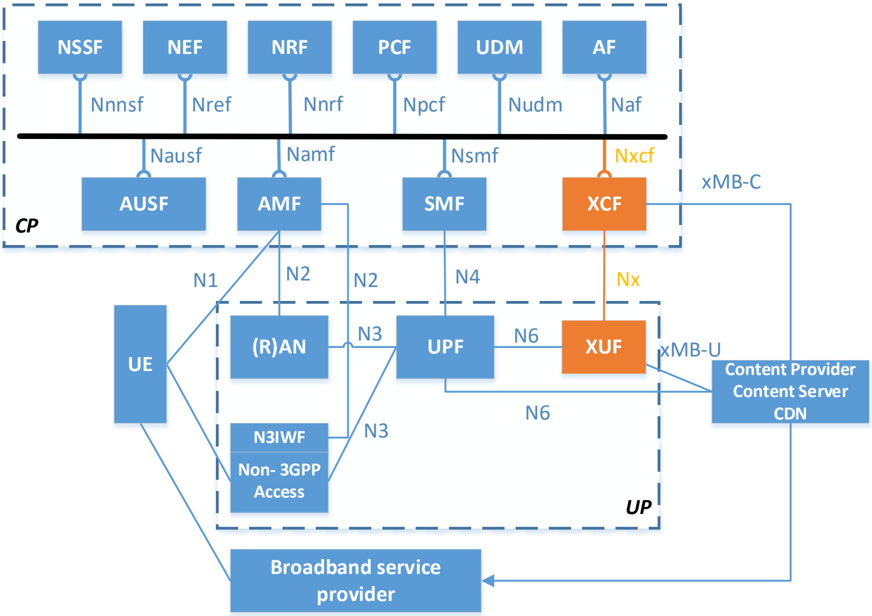


Figure 2.6: First proposed architecture in the 5G-Xcast project. Two new Network Functions, XUF and XCF, are introduced into the 5G Baseline system to provide Broadcast/Multicast capabilities. These Network Functions are connected between them over a new interface named Nx; while XCF is connected to the rest of the core over Nxcf. The UE may have dual connectivity features and is able to receive content from several networks.

The second architecture, shown in Figure 2.7, allows the XUF to directly interact with the RAN over the multicast-capable M1-NG interface, similar to the way that eMBMS works. The goal of this architecture was to provide a more gentle migration path and an architecture more focused with the delivery of point-to-multipoint services, like Terrestrial Broadcast. In this regard, the XUF must incorporate UPF features, like the management of gNB multicast groups and the multicast delivery using multicast protocols towards the RAN. Towards the CDN/public internet, the XUF has the same functionalities as the first version. Since the M1-NG is expected to have multicast capabilities, the eMBMS SYNC protocol could reside inside the XUF in order to provide a synchronization method for very large geographical areas composed of several gNBs. In a similar way, the XCF must incorporate SMF capabilities to manage the Broadcast/Multicast sessions. This architecture has a higher imprint when compared to the first one, as the new M1-NG interface would need to be implemented on the RAN side, so the gNBs are able to join and leave mul-

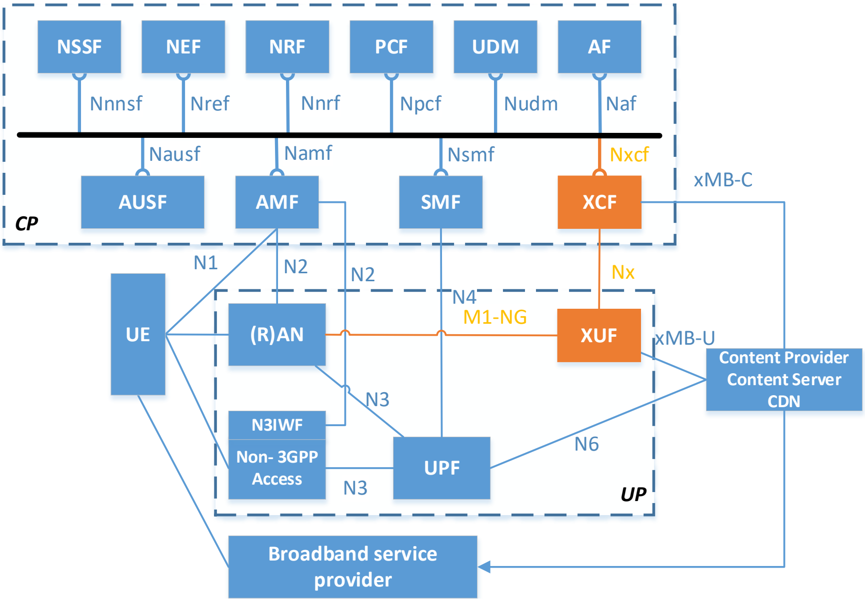


Figure 2.7: Second proposed architecture in the 5G-Xcast project. Two new Network Functions, XUF and XCF, are introduced into the 5G Baseline system to provide Broadcast/Multicast capabilities. These Network Functions are connected between them over a new interface named Nx; while XCF is connected to the rest of the core over Nxcf. The M1-NG multicast interface connects the XUF to the RAN, behaving similar to the LTE MBMS-GW. The UE may have dual connectivity features and is able to receive content from several networks.

ticast groups; but it presents a simpler migration way from existing eMBMS architectures and solutions into 5G ones.

2.3.2 5G-Xcast RAN architecture

The proposed 5G-Xcast RAN architecture is based on a Cloud-RAN principle, formed by just one gNB with elastic allocation of resources and connectivity [65]. This gNB follows the CU-DU separation paradigm [66] i.e. it is split between one gNB-CU and several gNB-DU. At the same time, each gNB-DU is connected to several RRH which contain the transmitter cells at the end, forming a tree-like topology. A diagram is shown in Figure 2.8. One of the requirements pursued is the capability to perform dynamic SFN broadcast/multicast communications, with the ability of transmitters to join or leave the synchronized transmission without incurring into service interruption. To do so, a new logical and User Plane based entity, called gNB-CU Multicast (gNB-CU-MC) is introduced inside the gNB-CU. To fulfil the SFN requirements, the RAN incorporates two main functionalities, one involving the Control Plane residing in the gNB-CU-C and the other related to the User Plane inside the gNB-CU-MC: The Control Plane part is the setup of the SFN area inside cellular networks, deciding the physical layer parameters such as modulation, code rate and scheduling to satisfy specific QoS. This decision is propagated using new signalling towards the relevant gNB-DU, which will relay this to the relevant RRH group. In addition, the gNB-CU can take into account existing unicast measurement reports such as channel quality to fine tune the physical layer parameters of the SFN transmission. The main functionality of the gNB-CU-MC is the constant encapsulation of the multicast data to provide TTA information for the cells involved in the SFN transmission. A modified eMBMS SYNC [31] is used as the encapsulation protocol, but instead of manually setting the SYNC parameters between the eMBMS Core and the eNBs over OAM, the parameters are negotiated in the SFN setup process of the gNB-CU. This revision of SYNC is called RAN-SYNC and is one of the main 5G-Xcast contributions. This approach simplifies the operating process and improves the deployment speed. Note that, in this case, the entity encapsulating the data resides inside the RAN, while in 4G eMBMS, SYNC is applied at the BM-SC.

In the proposed RAN deployment, the CU-DU separation allows RAN functions with higher layer processing like SDAP and PDCP to be placed at gNB-CU-MC for broadcast/multicast flows. The DU(s) closer to the deployed cells receive information about the SFN transmission parameters from gNB-CU-C and the gNB-CU-MC provides the broadcast/multicast traffic to DU for SFN transmission. The Layer 2 radio protocol architecture for Cloud-RAN defines that the RLC entities are located in DUs and DU controls the transport channels for the transmission, separating it from the same Cloud-RAN computing hardware pool as the gNB-CU-MCs. The gNB-CU-C configures gNB-CU-MC via E1 interface to trigger F1-M interface setup [59] for gNB-DUs which belong to the broadcast/multicast transmission list. Here the F1-M represents a logical interface between gNB-CU entity and a broadcast/multicacast capable gNB-DU, where the interface can be a unicast or a multicast tunnel of broadcast/multicast radio bearer, e.g. GTP-U over IP multicast. The gNB-CU-MC acknowledges tunnel establishment for the requested SFN radio bearers and monitors the status of existing ones, exposing this data to OAM. The switching of unicast tunnel to broadcast/multicast tunnel is permitted. More information on the logical channels and the SFN radio bearers can be found in [58] and [67].

The gNB-CU-C configures the associated gNB-DU with the SFN transmission parameters, including the transmit power, reference signal configurations

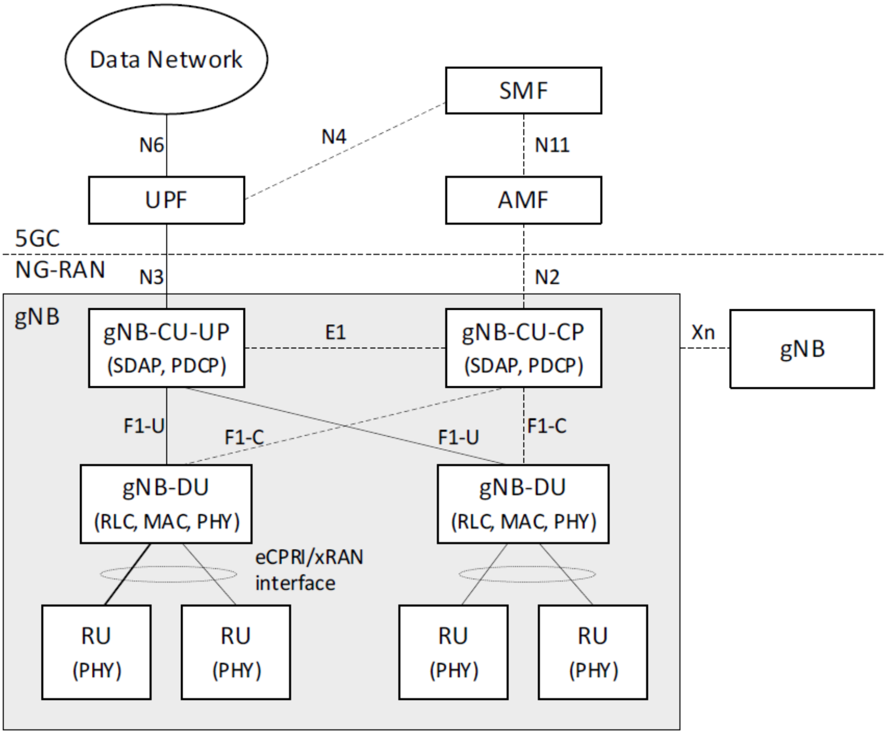


Figure 2.8: CU-DU functionality split in the gNB, with the standardized interfaces. Extracted from [65]

and possible subframes for broadcast/multicast transmissions. This enables the gNB-DUs to transmit the same data using the same physical radio resources thereby appearing as a single SFN transmission to the UE as shown in Figure 2.9. As the configuration takes place as part of the gNB-CU-C and gNB-CU-MC in NG-RAN, the pre-configuration characteristics of eMBMS is avoided. The 5G-Xcast RAN architecture fully leverages one of the main novelties of 5G: the replacement of QoS flows instead of Radio Bearers. By exploiting this, pre-assigned QoS flows for SFN can be defined in the 5G Core connected to the gNB, in order to trigger the SFN transmissions, allowing the multiplexing of unicast and broadcast data on the same radio sub-frames. Broadcast/multicast SFN transmission enabled gNB uses the SDAP layer where the modified gNB-CU-MC will receive the broadcast/multicast traffic and identify the type of traffic either based on the QoS flow identifier or through the context associ-

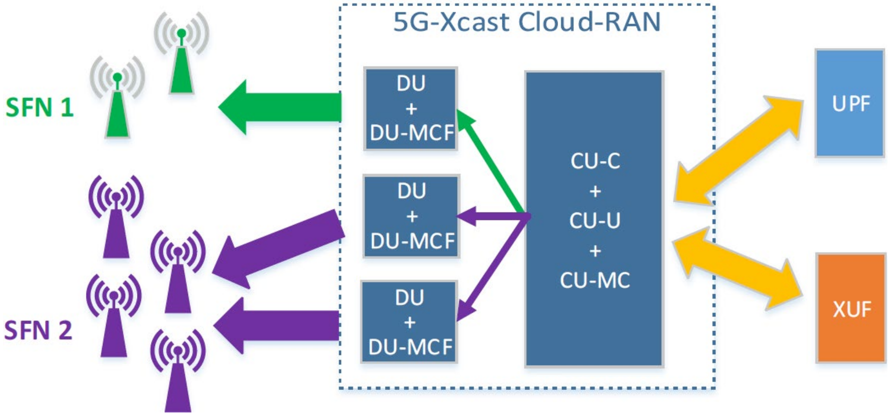


Figure 2.9: Architecture diagram of the proposed 5G-Xcast Cloud RAN solution. Two SFNs are shown, with different number of DUs involved in the synchronized transmission. The latency difference between different DU paths is compensated by using RAN-SYNC. Extracted from [68]

ated with the flow. In other words, there is a mapping between a QoS flow identifier and a broadcast/multicast service. In detail, the gNB-CU can dynamically configure (i.e. add, modify or remove) the gNB-DUs within the SFN service area based on the definition of SFN service area coverage and based on device feedback. The terminals are expected to provide neighbour cell measurement reports and feedback of the traffic it is receiving, which will allow the gNB-CU-MC to adjust the SFN coverage based, for example, in the device mobility and direction. The broadcast/multicast QoS flow can be also established as static, forbidding the gNB-CU-MC to dynamically modify the initial RRH group. This is useful for Terrestrial Broadcast, where the coverage studies tend to cover large geographical areas and devices are rooftop antennas. In summary, broadcast/multicast SFN networks in 5G-Xcast are identified by the session context, which holds information about broadcast/multicast QoS flows, bearers and the context is associated with a multicast group.

As previously said, RRH or transmitters involved in the SFN transmission can be attached or modified to dynamically created DUs. These dedicated DUs can deliver using multicast their broadcast/multicast packets to every transmitter pending from it, thus solving the static allocation limitation of geographical areas in eMBMS. In the case that one DU is overloaded by unicast and broadcast traffic, a new DU instance can be launched inside the gNB computation pool to share the load while migrating the context between different instances. Depending on the transmitters involved in the SFN, two different scenarios arise: either all transmitters are served by the same DU or the transmitters in the SFN belong to several DUs. The main implication derived from this is the divergence in packet processing time and distribution delay of the all possible data paths, which must be compensated in the TTA RAN-SYNC timestamps inserted by the gNB-CU-MC. On the one hand, for only one DU SFN scenario, only the difference in packet arrival time from several transmitters is relevant. On the other hand, for several DUs SFN, depending on the particular computational load and QoS parameters, a process time correction of broadcast packets must be added on top of the packet arrival time difference. The SFN context should be flexible enough for the RAN-SYNC parameters to be adjusted in case new DUs are added or deleted of a given SFN. Regarding data acquisition for the UE, when the data is being transmitted over the PDSCH based on scheduling and transmission parameters, the corresponding Downlink Control Information (DCI) through the Packet Downlink Control Channel (PDCCH) indicates the Radio Network Temporary Identifier (RNTI) which the UEs can decode. In case of broadcast/multicast the Group RNTI is allocated to a group of UEs who may be receive only devices, or in case of dynamic SFN areas a group of UEs who have indicated their interest in receiving broadcast/multicast traffic. The use of G-RNTI allows any UE to receive the broadcast/multicast data over the PDSCH without needing new physical channels.

The performance of this proposed architecture is evaluated qualitatively, in terms of imprint over the 5G baseline RAN, radio efficiency, latency and dimensionality. In detail: 1) The highest imprint is caused by the inclusion of a new entity in the gNB-CU, the gNB-CU-MC, which features a new protocol, RAN-SYNC. The number of new interfaces, mostly F1-M between the gNB-CU-MC and the DUs, impacts directly the service integration and deployment complexity of the new broadcast/multicast system. The rest of interfaces are reused 3GPP ones. 2) Radio efficiency is improved, in terms of capacity and cell edge coverage, since SFN transmissions turn destructive interferences at cell edge into constructive ones. In downlink-only transmissions, the number of UEs receiving a service is independent of the radio resources used, which would be the case for semi-static SFN areas, e.g. Terrestrial Broadcast Networks. However, if channel quality reports are allowed, which are needed for dynamic SFNs, the uplink resource allocation done per UE imposes an upper bound in the total number of UEs served under one cell, degrading the scalability features of broadcast. 3) In terms of dimensionality, the architecture follows a treelike topology, where one gNB-CU with a gNB-CU-MC serves a large amount of gNB-DU over F1 interface, and the gNB-DUs serve a large amount of RRH/cells. In [69], it is specified that the maximum number of gNB-DU under one gNB-CU allowed by the signalling is $2^{36} - 1$, and the maximum number of cells under one gNB-DU is 512 or 2^9. Overall, the maximum number of cells served is $(2^{36} - 1) * 2^9$.

Chapter 3

Convergence of Terrestrial and Mobile Networks

3GPP had introduced eMBMS as a solution to Mobile Broadcasting inside of 4G Mobile Networks; and repeated this exercise in Release 17 for 5G Mobile Networks as an optional extension of the baseline core. Their approach is based on the extension of the Core Network with broadcast capabilities, in a ”one size fits all” type of design. Chapter 2 covered the efforts previous to Release 17 in order to provide Mobile Broadcasting. Meanwhile, chapter 4 will cover the efforts of 3GPP in providing Mobile Broadcasting as part of Release 17. This chapter takes a different angle to the provision of Mobile Broadcasting, analysing the possibilities for existing Terrestrial Networks, infrastructure and waveforms to be used altogether with MNOs, instead of having all the broadcast functionality residing as optional modes of mobile technologies. In this new paradigm, the role of multimedia services can be expanded with new features and functionalities that fully leverage both the Terrestrial and Mobile Networks; effectively turning into Convergent Services. The joint use of Terrestrial and Mobile Networks is known as infrastructure convergence, and it is a complex issue with many different aspects of the convergent ecosystem that need evaluation, including technology, standardization, regulation, spectrum, business models, services and type of multimedia content. The analysis and evaluation of Convergence of Terrestrial and Mobile Networks has been focused in the joint use of ATSC 3.0 DTT standard alongside 5G to enable Convergent Services. The rest of the chapter is structured as follows: 3.1 provides an introduction to the concept of Convergence, with the motivation and fundamentals behind the idea; 3.2 explains what tools are available inside 3GPP and more specifically in 5G to support infrastructure convergence; 3.3 details the deployment options for enabling Convergent Services in joint ATSC 3.0 plus 5GC deployments, and the current technological limitations. The chapter closes in 3.4 with a proposed solution, based on QUIC dual connections, that overcome the existing 5G-ATSC 3.0 limitations.

3.1 Introduction to convergence

Mobile broadband networks need to respond to an ever increasing demand for data, mostly composed of multimedia video. A point-to-multipoint system that use efficiently the radio resources required to deliver multimedia based on user demand could solve this problem in the long-term. One solution is to equip Mobile Networks with a point-to-multipoint mode as an extension of current capabilities, that responds dynamically to user demand. Other solution would be to leverage other access networks and infrastructure, such as Terrestrial Television Networks. In a cooperation agreement, MNOs and Broadcast Network Operator (BNO)s can interconnect to each other, benefiting from the implicit characteristics of each different access networks, and deploy new or evolved services that utilize the best properties of each network.

Traditional broadcast services are identified with linear content and point-to-multipoint transmissions; in which BNOs own the necessary infrastructure, usually HPHT, to deliver multimedia content for roof-top antennas in a efficient and scalable way. Sometimes, this doesn't happen, the transmitter infrastructure is not directly operated by the BNO, but by a third party, in the figure of a neutral host or tower provider. Video consumption has been evolved hand in hand with consumer behaviour. It is widely accepted that people expect more features from their TV experience than just watching linear broadcast programs. First, they want on-demand services so that they can watch the content whenever they want. Second, they want to watch TV anytime, anywhere and regardless of the device type. It could be on a wide-screen TV in a living room or on a handheld device such as smart phone or tablet. The trends of TV consumption patterns like on-demand, mobile, and Ultra HD quality imposes formidable challenges for the broadcast of the future [70], suggesting that it will be quite similar to the mobile broadband in many aspects [71].

Table 3.1, extracted from [70], shows the strengths and weaknesses of each network type. It is clear that a symbiotic relationship between BNOs and MNOs could be possible, where Convergent Services which use both networks are improved in terms of quality and reliability. BNOs could profit from giving new uses to the spectrum licenses they own, by renting or leasing it to MNOs (if the local regulation permits it), so MNOs gain access to extra downlink-only bandwidth. In the case that the BNO and the MNO decide to share

Table 3.1: Strengths and Weaknesses for BNOs and MNOs. It can be seen that the weaknesses of BNOs can be covered by the MNOs, and vice versa

	Strengths	Weaknesses
BNO	Almost universal coverage Different reception modes Assured QoS Optimized for linear delivery Cost does not scale with number of users Network congestion is not possible	Return channels are standardized, but not deployed commercially Cannot deliver VOD content
MNO	Bi-directional communications Optimized for mobile reception Any service can be delivered Fit for niche or long tail services	Capacity variable of cell distance Best effort QoS Cost does scale with number of users Network congestion is possible

infrastructure; BNOs delivering Convergent Services can increase their potential audience by reaching mobile terminals; while MNOs gain the benefit of extra coverage and the possibility of efficient traffic offload. To exemplify this concept, a Convergent Service could consist of a dual connectivity device, that is consuming a Linear TV programme. In the case that some broadcast packets are erroneously received, they are retransmitted using a mobile link so the device can correct the video before it is displayed on screen[72]. Nevertheless, the joint use of Broadcast and Mobile Networks and provision of Convergent Services is not trivial, as there are challenges to overcome. In [73], 4 major hindrances that limit the provision of Convergent Services are identified and detailed. They are: Technology, spectrum, regulation, and business models. Following subsection will provide more details on the fundamental aspects of convergence. More information regarding the challenges can be found in [73].

3.1.1 Fundamentals of Convergence

The efforts made by the ETSI Mobile Broadcast Convergence Group, or ETSI MBC, were focused in analysing the current landscape for infrastructure convergence and Convergent Services, where the communications are performed over two infrastructures: one of them Broadcast, and the other a Broadband one, be it non-terrestrial, fibre or mobile networks. ETSI MBC asserted that, technology wise, there are three main ways to provide Convergent Services [73]. They are shown in Figure 3.1 and are detailed next:

- **Convergence of network infrastructure**. A combined network infrastructure is assumed as the enabler for Convergent Services, which incorporates different telecommunication technologies such as terrestrial, satellite, fiber and fixed links; all managed and operated from a single operator. The main feature to be exploited is dynamic switching between different communication modes such as unicast, multicast and broadcast. This is also known as Traffic Switching in 3GPP terminology. This switching would be performed based on the network traffic, link quality and specific requirements of the service. The complexity of this convergence option resides in the routing and management of traffic through the different accesses of the converged network. One example of this approach is the 5G-Xcast Converged Core Architecture [54], which is described in detail in chapter 2.

- **Seamless interoperability**. This convergence case is characterized by an heterogeneous network infrastructure, formed by two (or more) access networks, which can seamlessly interoperate thanks to common communication protocols over interconnecting interfaces. Control over content distribution lies with different entities in the distribution ecosystem, i.e. each network is operated and managed by a different stakeholder. Traffic routing is possible but requires corresponding peering relations and additional measures to ensure that the QoS is maintained across accesses. An example of this approach is the Tower Overlay trials based on the joint use of DVB-T2 and LTE [74].

- **Device-based convergence**. This assumes that the Convergent Services are enabled on the user device. The devices feature several network interfaces and has the ability to connect to different networks simultaneously. The software or middleware controlling these interfaces is tasked with the combination of the traffic flows received through different distribution infrastructures. In this situation, it is the over-the-top application and the middleware in the device who are performing the management of the Convergent Services. As such, the network operator may be unaware that applications are delivering flows over several access networks and apply the usual QoS rules to the broadband flow. For instance, Electronics and Telecommunications Research Institute (ETRI) performed field trials based on a dual ATSC 3.0 - LTE receiver [75].

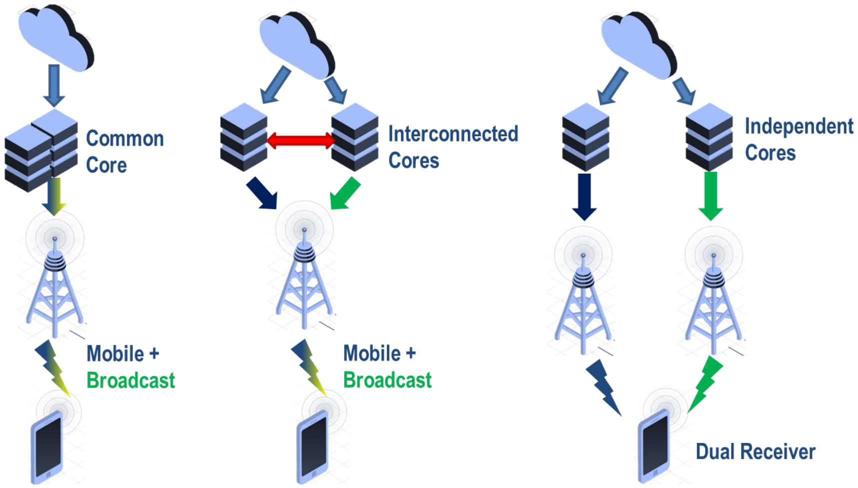


Figure 3.1: Three types of Broadcast and Mobile convergence, extracted from [73]. Whereas in convergence of network infrastructure (left) both systems share a common core network, two independent but interconnected core networks are used in the seamless interoperability mode (center). Device-based convergence (right) needs a more dual receiver device with one for mobile and one for broadcast

Convergent Services are also characterized by the Layer in which the convergence happens. That is, in which part of the protocol stack the service packets are split or switched to different infrastructures (or to same infrastructure in case of Layer 1 convergence). Three alternatives have been the most used for existing convergent experiments: Layer 1 or Physical Layer; Layer 3 or Transport IP Layer; and Layer 7 or Application IP Layer. Layer 1 convergence is based on the reuse of the same spectrum to accommodate both mobile and broadcast services. This allows for the reuse of mobile or broadcast infrastructure for different type of receivers (or the same receiver if it can support both services). There are two main ways to enable Layer 1 convergence, the first is by sharing the waveform for both mobile and broadcast; while the second multiplexes in time or power the mobile service frames with broadcast services frames. An example of Layer 1 convergence would be eMBMS (or the 5G version, 5MBS), where the same LTE signal accommodates both unicast and broadcast subframes; even use the unicast part of the signal to deliver lost or erroneous packets [76] or gather consumption reports [77]. Another example includes the use of Layer Division Multiplexing mode of ATSC 3.0, where the total transmit power of the broadcast signal is divided into two: One for a low power, reliable and low capacity service better suited for indoor and mobile reception, and the other being a high power layer targetting rooftop antennas. The main advantage of using Layer 1 convergence is that only one infrastructure is necessary to serve both mobile and broadcast services; without incurring in complex management of several access networks or collaboration agreements between MNOs and BNOs. On the other hand, the reception quality may be compromised, as the characteristics of MNO and BNO deployments and their target devices is different. A broadcast signal radiated from an urban Lower-Power Low-Tower (LPLT) deployment could have coverage issues against rooftop antennas. Note that this type of convergence is complementary to Layer 3 convergence, where different parts of the same waveform carry segments of a Convergent Service, identified by a single IP.

Layer 3 convergence is based on the application of specific actions to the service packets inside the transport network and two different access networks. These include packet steering, switching or splitting; which will mandate the characteristics of the Convergent Service. As the packets are forwarded or split, the source IP remains constant, so the end device can still identify each different flow as part of the same service. The transport network can take the decision to steer or switch service packets based on metrics gathered for each access network, which already happens in the 5G ATSSS framework. For example, a BNO providing a Scalable Video Coding (SVC) transmission, defined by a Base Layer and Enhancement Layer [78], radiates the Base Layer with standard quality freely in a wide area. In order to improve the video quality by offering a premium and paid service, the BNO has reached an agreement with a MNO, where MNO clients can buy a premium 4K-quality service, in which the Enhancement Layer required to upscale the content is delivered via mobile infrastructure. In this case, the Convergent Service has a Layer 3 convergence, since the Base Layer and the Enhancement Layer are routed to different networks. The software displaying the SVC video is able to identify that the packets coming from different networks thanks to the IP of the service, which is shared for both SVC Layers. Layer 3 convergence leverages IP-based infrastructure in a seamless way. Assuming that the same operator manages both Broadcast and Mobile Network, different transmitters are just identified by their own IP addresses and can be easily reached by the Convergent Service. This is the case for the Convergence of Network Infrastructure deployment model shown in the left part of Figure 3.1. On the contrary, if two stakeholders are operating and managing their own network, it is necessary to provide additional interfaces, protocols and policies between the two actors to ensure Seamless Interoperability, as pictured in the middle diagram of Figure 3.1.

On the other hand, Layer 7 convergence is an application based optimization, where the content provider uses several links to enhance the quality or reliability of the Convergent Service. As pointed out earlier, this is Device-based convergence [73]; where it is the actual middleware inside the device which recombines or enhances the service coming from several accesses. In this scenario, the BNO and MNO do not perform any special type of operation and do not require any kind of special collaboration agreement between them or with the end user; as the user just uses public MNO infrastructure to enhance their service. The main advantage of this type of convergence is that agreements and planning between end user, MNO and BNO are not necessary; since these Convergent Services perform all the complex decisions at the application on the side and at the display on the other side. As drawback, the quality of the service flowing through public MNO channels cannot be guaranteed as these networks are best-effort. As an example of a Layer 7 Convergent Service, a BNO or content provider delivers immersiveness or extra information (e.g. Name of the cast appearing in the current scene) to a live broadcast content using an extra broadband connection, be it a mobile wireless one or home broadband. This is the basis of Hybrid Broadcast Broadband Television Standard (HbbTV) technology [79].

3.2 Convergence in 3GPP

The concept of convergence is not novel for 5G. The first 3GPP standards considering multiple accesses began with 3G [80]. The standardization group classifies the different access networks in two broad categories: 3GPP networks, such as Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE), and 5G; and non-3GPP networks, which includes any wireless or wired communication network, such as Wi-Fi, Wimax, DOCSIS... It is noteworthy that most of 3GPP convergence efforts were focused into the interworking of Wireless Local Area Network (WLAN) technologies alongside 3GPP systems. Derived from this, any effort to include non-bidirectional, non-3GPP networks convergence or interworking alongside 3GPP networks will face severe limitations and challenges to overcome, as the current standards expect both technologies to feature full duplex capabilities. Other fundamental concept is the designation of non-3GPP Trusted Access (Trusted Convergence) and non-3GPP Untrusted Access (Untrusted Convergence) [1]. Trusted Convergence occurs when the MNO has full control of both the non-3GPP and 3GPP access. 5G UEs are capable of subscribing, authenticating, sending and receiving data over the non-3GPP access. This implies a full reuse of the 5G Core Network

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[1] From now on, any use of the term Trusted Convergence is equivalent to non-3GPP Trusted Access; and any use of the term Untrusted Convergence is equivalent to non-3GPP Untrusted Access

to manage every data flow and session under 3GPP and non-3GPP networks. Advantages of using Trusted Convergence is that both non-3GPP and 3GPP access can be configured independently, enforce customized policies for each transmission technology, and operate on different licensed or unlicensed spectrum bands, all managed by a single Core Network. Untrusted Convergence, on the other hand, occurs when part of the non-3GPP access network is outside the MNO jurisdiction, usually belonging to a third party. The main motivation behind this feature is enabling Wi-Fi devices supporting 5G signalling, to attach into a 5G Core Network using their non-3GPP link managed by a third party and guaranteeing the integrity and ciphering of the data end-to-end using IPsec tunnels. In case that the MNO collects any user metrics, it can be exposed via Network Exposure Function (NEF) to third parties, for example, to perform network optimization. E.g. metrics with signal quality can be stored in a database hosted by the MNO and this database exposed to the third party via NEF and a dedicated API.

Depending on the convergence type, additional extra NFs will need to be deployed [81] and shown in Figure 3.2. In the case for Untrusted Convergence, 3GPP have specified a new entity, called N3 Interworking Function (N3IWF) that manages all the required procedures to authenticate, encrypt and forward data to external non-3GPP networks. The main task that the N3IWF performs is the termination of IPsec tunnels between non-3GPP modems and the 5GC. The N3IWF resides inside the 5GC and interfaces with the AMF over the N2, and translates the non-3GPP modem signaling into appropriate messages for the N1 interface. At the data plane, it communicates with the UPF over the N3 interface, similar to a baseline gNB. On the other hand, Trusted Convergence will require two additional NFs: the Trusted Non-3GPP Gateway Function (TNGF), which will connect with the Wi-Fi devices, exchanging 5G NAS messages over the NWt interface, and with the 5GC control plane over the N2 towards the AMF (in this regard, the TNGF is seen as a gNB to the AMF), and N3 interface to the UPF. It is notable that between the Wi-Fi device and the TNGF, a NULL IPsec connection will be deployed, to ease implementation in Wi-Fi devices that support 5G connections. The second NF is the Trusted WLAN Interworking Function (TWIF), introduced for backwards compatibility, in case some devices support 5G authentication but not the full signaling suite. In this case, on top of providing the N2 connectivity to the AMF, the TWIF translates the signaling coming from the UE into 5G non-access-stratum compliant messages which will be carried over the N1 interface. These type of devices are known as non-5G-Capable over WLAN.

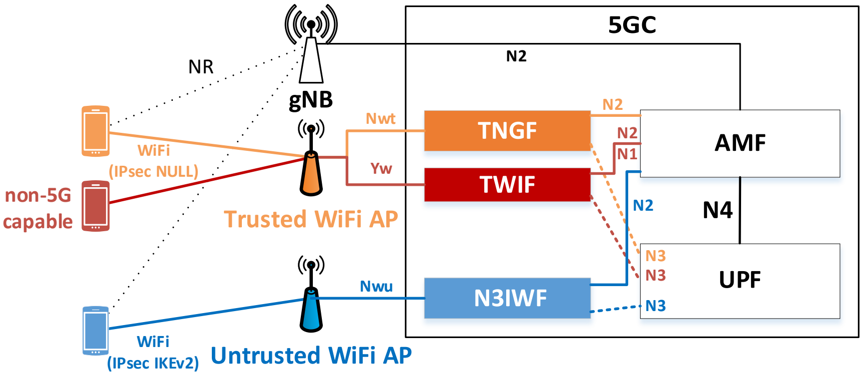


Figure 3.2: Different standardized possibilities for Trusted Convergence and Untrusted Convergence [81][82]. Depending on the device 5G and Wi-Fi capabilities, different connections modes are possible. TNGF is used for Trusted Convergence, when the device supports the full 5G over Wi-Fi functionality. In the case that the device does not support the Non-Access Stratum protocol, it would connect to the TWIF instead, and the TWIF will create the correspondant N1 signalling. N3IWF is used when the device is using an external Wi-Fi to connect into a 5G network.

The second step to enable Convergent Services is having a framework that leverages multiple access networks. This framework exists and it is known as Access Traffic Steering, Switching and Splitting or ATSSS. It began as a Study Item during Release 15 [83] and introduced into 5G standards in Release 16 [84]. ATSSS motivation is to integrate Wi-Fi and wireline access networks into the 3GPP ecosystem, reusing existing control plane functionality and centralize the management under one core. The pictured scenario is one where the MNO is offering both residential internet and wireless connectivity bundled plans to their customers, and want a single core network to manage both, instead of two independent connectivity solutions. It is noteworthy that there is no mention of supporting a broadcast, unidirectional non-3GPP access into ATSSS nor it was considered as a possible extension topic. The main outcome of this SI was two-fold: the definition of ATSSS operational modes (Traffic Steering, Traffic Switching and Traffic Splitting); and the classification of non-3GPP Trusted Access and non-3GPP Untrusted Access. The initial scope of this proposal is detailed next:

- How the 5G Core network and the 5G UE can support multi-access **traffic steering** between 3GPP and non-3GPP accesses. Steering is the procedure that selects an access network for a new data flow and transfers the traffic of this data flow over the selected access network.

- How the 5G Core network and the 5G UE can support multi-access **traffic switching** between 3GPP and non-3GPP accesses. This includes the conditions that can trigger the switching of data traffic to a new access type.
- How the 5G Core network and the 5G UE can support multi-access **traffic splitting** between 3GPP and non-3GPP accesses (known as multiaccess PDU session). This includes the conditions that can trigger the splitting of data traffic across multiple accesses.
- How ATSSS can be taken into account by the charging framework in order e.g. to enable the network operator to differentiate charging for data traffic that is switched and/or split between 3GPP and non-3GPP accesses.
- How the 5G core network can support multiaccess PDU sessions, i.e. PDU sessions whose traffic can be sent over 3GPP access, or over non-3GPP access, or both.

As previously mentioned, ATSSS is mainly characterized by three different operations between 3GPP and non-3GPP accesses: Traffic Steering, which is choosing the best network, based on different metrics, to deliver the user data. Traffic Switching is changing an on-going data transmission to one access network into another, minimizing the service interruption. Traffic Splitting is dividing the packets from a data flow into each access network to enhance either the bandwidth and data throughput, or the reliability by sending the same content twice. To enable ATSSS, new functionality is introduced into the existing baseline 5G system architecture, as shown in Figure 3.3. The existing AMF, SMF and PCF are extended with new functionality. A new set of multiaccess policy rules is defined and stored in the PCF, which the SMF will share with the UE to shape the uplink traffic. Similarly, downlink multiaccess traffic rules are delivered from the SMF to the UPF via N4. The UPF manages the new Multiaccess Packet Data Unit (MA PDU), which will contain a pair of N3 and N9 interfaces, one defining the 5G connection, and the other the non-3GPP one. To check the available access networks quality, the UPF interfaces with the ATSSS specific Performance Measurement Function (PMF). The PMF recollects network and UE data to derive performance measurements for every link involved in the convergent transmission and decide to apply changes to the policies if necessary. There are two types of ATSSS delivery modes to distribute access traffic: Higher layer ATSSS based on Multipath Transport Control Protocol (MPTCP) [85], and Lower Layer or ATSSS-LL. The UE and the UPF must support at least one ATSSS delivery mode and optionally may support both. Note that, depending on which ATSSS delivery mode is being

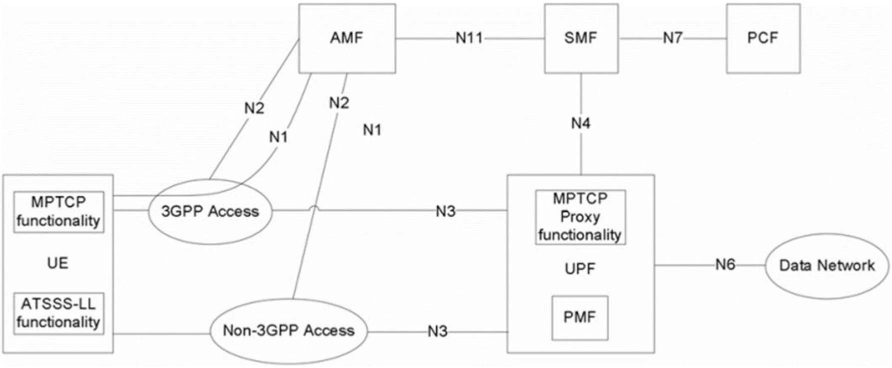


Figure 3.3: ATSSS functionality included in the 5G System [84], including the User Equipment (UE). On top of the baseline 5G Core, ATSSS extensions include the Multipath TCP (MPTCP), Performance Measurement Function (PMF) and the ATSSS Lower Layer modules.

used, some ATSSS operations are may not available. Using MPTCP enables traffic steering, switching and splitting, while ATSSS-LL only allows for traffic steering. The choice of the delivery mode used will depend on the target device, the Convergent Service requirements and the type of access networks being converged.

3.3 ATSSS-enabled convergence between ATSC 3.0 and 5G

The focus of 3.3 is to answer if the 5G feature ATSSS, as currently defined in the standards, is enough to enable Convergent Services over broadcast and mobile networks or additional work is required. ATSC 3.0 [86] was selected as the broadcast technology to be converged with 5G ATSSS. As explained in 3.1, a BNO and MNO can establish a symbiotic relationship and provide Convergent Services. ATSC 3.0 shares many technologies with 5G [87]: Both are totally IP-based, have similar physical layers, support for non-orthogonal modulations, etc... In ATSC 3.0 networks, most of the intelligence resides in the ATSC 3.0 Gateway. This component performs several functions, including the processing of inputs (e.g. Real-time Object delivery over Unidirectional Transport (ROUTE), MPEG Media Transport Protocol (MMTP) multimedia services, and Lower Layer Signalling (LLS), Service Layer Signalling (SLS) signalling into baseband frames or ATSC Link-Layer Protocol (ALP) streams), scheduling, providing synchronization and timing information to create and keep SFN, and management features for Broadcasters to monitor the on-going services. This section focuses on both the possibilities of having Trusted Convergence or Untrusted Convergence at Layer 3 (IP) and proposes possible deployments for both. To do so, a limitations list regarding the provision Convergent Services using ATSC 3.0 and 5G is shown, based on the Release 16 version of the ATSSS framework.

3.3.1 Limitations of ATSSS for ATSC 3.0-5G Convergence

The use of ATSSS technology for joint use at an IP level of ATSC 3.0, a broadcast-only technology, alongside NR; poses several challenges. Existing commercial solutions for ATSSS are manufactured to converge Wi-Fi and NR, expecting full connectivity from both access networks. When a 5G link is paired with a one-way only non-3GPP access, some of these technologies and procedures no longer work. The previous section established that there are two ATSSS delivery modes in Release 16, MPTCP and ATSSS-LL. MPTCP is based on establishing multiple TCP links between a content source and the destination device; and those TCP links require constant acknowledgements and retransmissions over every link involved. When one of those links is a broadcast-only channel, such as ATSC 3.0, it cannot deliver back the correct reception of packets, limiting the usefulness of MPTCP as an ATSSS delivery mode. One way to solve this problem is to use the duplex 5G NR channel as both uplinks for the NR channel itself and the ATSC 3.0 signal; however, there are no standardized means to perform this operation, i.e. 3GPP has not defined logical and transport wireless NR channel to carry specific non-3GPP channel quality and status data. On the other hand, ATSSS-LL is quite limited in the support of ATSSS operations. As it does not feature any managing procedure on top of the existing protocol stack, the only ATSSS operation possible is Traffic Steering, which is perform before a connection is setup. In case that a Convergent Service needs to perform an access network change, the service itself would need to be stopped, launched on the other access network, and the devices reconnect to the transmission. Support for Traffic Switching and Splitting can be provided with specific software updates, but these upgrades need to be bilateral between the 5GC and all devices in the network. 3GPP leaves this topic open for manufacturer implementation.

Another importation limitation of ATSSS is how Untrusted Convergence is defined. Devices connected to a non-3GPP network first need to deploy an IPsec tunnel to the N3IWF, which will validate the 5G credentials against the AUSF. Then, after the 5GC have authenticated them, they can use the Convergent Services over 5G and the non-3GPP network. When applied to ATSC 3.0, this raises a problem, where the downlink-only nature of the ATSC 3.0 transmission is unable to carry the required handshake to setup the IPsec tunnel. A standard compliant 5GC would reject any N3IWF connection incoming from the NR side for security reasons, so the non-3GPP network link cannot be ever setup. Changes in the 5G standard to allow for non-3GPP network availability over NR would need to be allowed, to enable flexible ATSSS operations in Untrusted Convergence deployments. On top of the aforementioned limitation, all the traffic forwarded in the N3IWF towards the non-3GPP network will be encrypted as it enters the IPsec tunnel. One of the main characteristics of broadcast is the free-to-air, where any receiver or TV can simply tune to the signal without the operator or broadcaster involvement. If the programmes are being radiated encrypted due to the N3IWF, the free-to-air property is lost, as the keys would need to be stored preemptively in the display devices that do not feature 5G capabilities. The current N3IWF release does not support NULL or plain IPsec tunnelling, so this encryption cannot be disabled and it is mandatory in Untrusted Convergence. A way to overcome this limitation is proposed in section 3.4, where the IPsec tunnel is ended in the ATSC 3.0 Gateway so devices do not deploy the tunnel themselves. By doing so, the Convergent Service can be radiated plainly. The last limitation is the lack of synchronization methods for 5G and non-3GPP networks. Since the waveform for each wireless access is different, a situation during Traffic Splitting could appear where the low latency modes of NR are not compatible with long ATSC 3.0 frame structures. In the most extreme example, a NR waveform is configured with a short Time Transmission Interval of 1 ms, while the ATSC 3.0 connection has long LDPC codewords, Time Interleaving enabled, and several Physical Layer Pipes, which introduce further latency at the decoding process. A way to overcome this is to enhance the receiver physical memory for larger buffer sizes, so this difference in decoding latency between access networks can be compensated, but it will make ATSSS receivers more expensive and complex.

The limitations found are summarized next:

1. ATSSS MPTCP requires two fully connectivity paths in order to ensure that the packets across networks are being delivered correctly. However, by intrinsic nature of being broadcast, ATSC 3.0 radio network cannot deliver uplink packets; making MPTCP unviable as a convergent technology.

2. ATSSS-LL does not implement any overlaying protocol in order to provide traffic switching between paths nor splitting mechanisms. This means that, devices and cores implementing ATSSS-LL are limited to Traffic Steering.

3. Untrusted Convergence, has procedures defined in 3GPP to enable the dual connectivity: It is expected that the device will connect first to the non-3GPP radio network, then deploy an IPsec tunnel towards the interested N3IWF from the 5G operator. This is not possible in ATSC 3.0 as it does not have an uplink channel.

4. N3IWF is expected to encrypt content which is leaving the 3GPP network. In a point-to-multipoint system, encrypted content is problematic since the decryption key must be known by every user in a priori manner, or the content be decrypted before being radiated by the ATSC system; as N3IWF does not support unencrypted communications.

5. There is no synchronization protocol to coordinate non-3GPP and 3GPP radios. In case of traffic splitting, this requires more buffer memory of the receiver in case that each path experiences different latency, configuration differences and decoding time.

6. Rerouting ATSC 3.0 Control Plane signalling and messages via 5G is not supported, since there is no transport or logical channel allocated to deliver non-3GPP messages via NR. If this limitation is overcome via standardization, NR can become the uplink part of the ATSC 3.0 path.

3.3.2 ATSC 3.0-5G Trusted Convergence

To enable ATSC 3.0-5G Trusted Convergence, the 5GC must incorporate the ATSC 3.0 Gateway functionalities [88]. This could be enabled by introducing extra NFs into the 5GC. However, these broadcast functions should also comply with one of the main principles of 5G: the Control Plane and User Plane separation. Derived from this, the ATSC 3.0 Gateway must be split into functionalities, depending if they are control based or data based: Preamble, Timing and Management information will form the Control Plane of the ATSC 3.0 GW or Control Plane Gateway Function (CPGWF); while Data Forwarding and ALP formatting constitutes the User Plane of the ATSC 3.0 GW, called User Plane Gateway Function (UPGWF). In summary, the CPGWF features the Control Plane aspects of ATSC 3.0 and the UPGWF, which can be co-located with the UPF; are necessary to support the inclusion of ATSC 3.0 capabilities into the 5G Core. These new NFs connect to the rest of the core using two new interfaces: *Natscc* and *Natscu*. Natscc is an SBA-based interface, which follows the RESTful paradigm [89] while leveraging the SBA features of 5G. It can inherit all the existing functionalities of the Naf interface [90] to expose its capabilities and broadcast session status. In this regard, other entities such as the SMF or AMF could request particular broadcast information from the

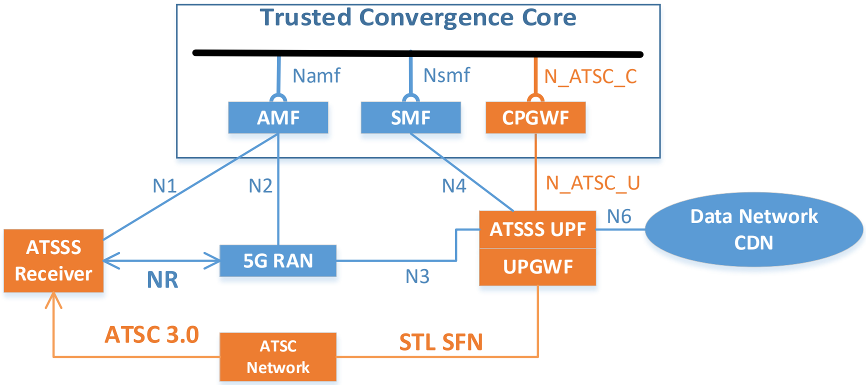


Figure 3.4: Proposed 5G Core deployment for Trusted Convergence, using the ATSSS framework. While Trusted non-3GPP Access in 3GPP requires the deployment of either TNGF or TWIF, this can be omitted since the devices cannot connect to the 5GC using the non-3GPP access, ATSC 3.0.

CPGWF, such as status and geographical area of the broadcast transmissions, while using 5G compliant API calls to deliver this info over Natscc. Natscu connects the CPGWF to the UPGWF, and it is used to deliver the broadcast session information (e.g. geographical area), the LLS and the timing configuration. All this information is required to form the ATSC 3.0 baseband frames and manage the SFNs transmissions.

Trusted Convergence requires a primary 5G connection from the devices, then the network will announce the possibility of using secondary access points and which services are being radiated. This implies that in order to benefit from convergence, display devices will depend on their 5G connection to discover possible ATSC 3.0 service enhancements. This can be leveraged, as the devices will never perform an attach over the ATSC 3.0 network. There is no need to include a TNGF nor TWIF, so the UPGWF can directly forward data to the ATSC 3.0 exciters using the STL/SFN interface. Regarding ATSSS in this new architecture, and mentioned by the previous limitations, the only valid mode for ATSSS convergence is using ATSSS-LL. By default, this mode will only allow for Traffic Steering, limiting the possibilities of Convergent Services. The 5G Core Network would only be able to choose how to deliver a given content, either over 5G or ATSC 3.0, but not be able to switch in real time from one to another. The decision to use one network over the other access can be optimized, thanks to the metrics provided by the 5G terminals. The devices who are tuned to Convergent Services can also deliver signal quality and audience reports back to the ATSC 3.0 Gateway in order to optimize the broadcast transmission, taking in mind that there is no standardized way to do so. The management and orchestration of the two different infrastructures is centralized. Since the convergence happens at IP level, one UPF with SDN enabled capabilities could easily forward the multimedia data to ATSC 3.0 Terrestrial Networks or 5G Radio Access Networks based on network conditions and without operator input. In the case that the MNO looking to offer Convergent Services has no access to ATSC 3.0 sites, the cellular nodes can be equipped with ATSC 3.0 radio heads [91] and be accessed using the same back-haul IP network as the 5G gNodeBs. The ATSC 3.0 waveform is flexible enough to accommodate urban and pedestrian scenarios with Low Power Low Tower deployments, sharing the same cellular sites but still using their own spectrum bands.

3.3.3 ATSC 3.0-5G Untrusted Convergence

This convergence case is characterized by two different networks and infrastructures, the 5G Core Network and the ATSC 3.0 Network, which are connected through interworking interfaces and feature Layer 3 IP convergence. The proposed convergent architecture, as shown in 3.5, is designed to deliver Convergent Services while overcoming ATSSS limitations. The solution features two access networks: the ATSC 3.0 infrastructure including the radio transmitters (typically HPHT deployment with gap-fillers), and one (or several) ATSC 3.0 Gateway, which perform the functionalities included in [88]. The 5G infrastructure, which is usually deployed as a dense LPLT, consists of a 5GC with ATSSS capabilities in the UPF, a NEF to expose the own capabilities and metrics to the ATSC network, and a 5G RAN. The ATSC 3.0 GW incorporates two new functional blocks on top of the baseline ones in order to enable convergent services: the 5G AF and the IPsec client. In detail, the 5G AF connects to the MNO NEF using the standardized API [90] in order to request and serve petitions to create, modify or destroy Convergent Services. The IPsec client is used to attach the ATSC 3.0 GW into the MNO 5GC via N3IWF, following the procedures in [92]. In this sense, the ATSC 3.0 GW is seen as an end device to the 5GC. This is done to terminate the encryption of the data before being broadcasted, identified as limitation 4); and allows dual devices attached to the 5G network to tune into the ATSC 3.0 at any time, overcoming limitation 3).

In the same vein as the Trusted Convergence, only ATSSS-LL would work in this architectural proposal. MPTCP needs both paths to reach the end device in order to ensure the correct packet receival at appropriate time intervals, asking for retransmissions if the packets are lost. Untrusted Convergence would end the MPTCP flow entering the ATSC 3.0 network at the ATSC 3.0

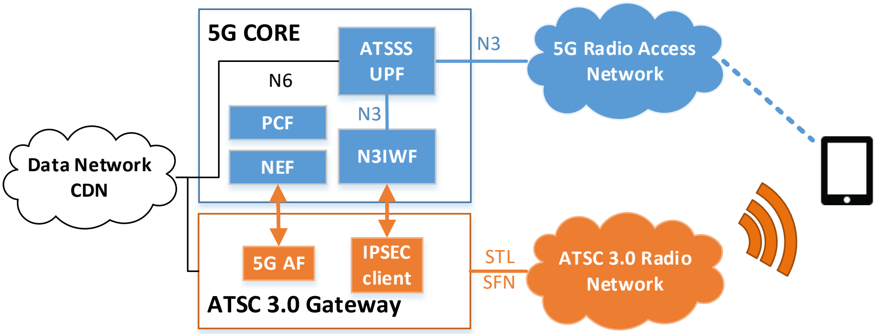
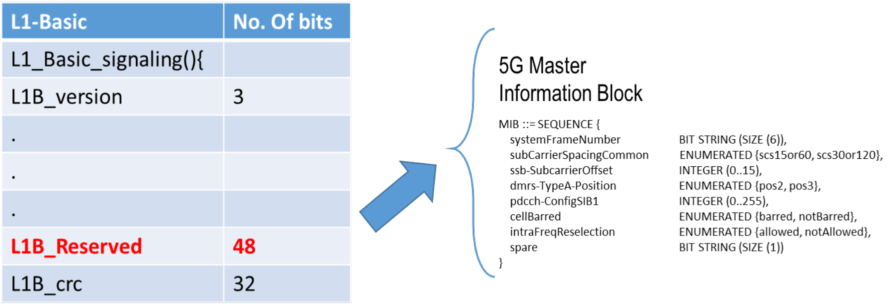


Figure 3.5: Proposed 5G Core deployment for Untrusted Convergence, using the ATSSS framework. The mandatory IPsec tunnel with the N3IWF is terminated at the ATSC 3.0 Gateway, which will allow for the multimedia content leaving the N3IWF to be radiated plainly. The ATSC 3.0 Gateway also incorporates an Application Function that will interact and expose capabilities with the 5GC NEF.



L1-Basic	No. Of bits
L1_Basic_signaling(){	
L1B_version	3
.	
.	
.	
L1B_Reserved	48
L1B_crc	32

5G Master
Information Block

```
MIB ::= SEQUENCE {
   systemFrameNumber                  BIT STRING (SIZE (6)),
   subCarrierSpacingCommon            ENUMERATED {scs15or60, scs30or120},
   ssb-SubcarrierOffset               INTEGER (0..15),
   dmrs-TypeA-Position                ENUMERATED {pos2, pos3},
   pdcch-ConfigSIB1                   INTEGER (0..255),
   cellBarred                         ENUMERATED {barred, notBarred},
   intraFreqReselection               ENUMERATED {allowed, notAllowed},
   spare                              BIT STRING (SIZE (1))
}
```

Figure 3.6: Example of using the L1 reserved fields of the ATSC 3.0 signalling to carry 5G MIB information. This would ease the reception of Convergent Services as 5G devices tuned to ATSC 3.0 broadcasts can attach to the 5G Network faster.

Gateway, so the TCP headers would never be radiated nor reach the devices. By using ATSSS-LL, the only ATSSS operational mode available is Traffic Steering, where the 5GC can choose what network to deliver data into, be it its own 5G network, or the broadcaster ATSC 3.0 Network. By itself, trying to switch an on-going transmission from mobile into broadcast will incur into service interruption. Another innovation to enhance the reception of Convergent Services is the delivery of 5G information inside the ATSC 3.0 signalling. The two low level signalling in ATSC 3.0, L1-Basic and L1-Detail, have some reserved bits for future use. These reserved fields in L1-Basic and L1-Detail can accommodate the 5G MIB and a small number of SIBs, allowing devices to quickly tune and find the associated 5G network which will deliver the Convergent Service. Legacy receivers without 5G capabilities would ignore these Reserved Fields, but the ATSC 3.0 Gateway should ignore the 5G signalling for the CRC calculation for full backwards compatibility. It is shown in Figure 3.6.

3.4 QUIC-enabled Convergence

The previous section showcased two possibilities to deploy a 5GC convergent with an ATSC 3.0 Gateway. It was shown that both, in terms of Release 16 ATSSS operations, are quite limited. As MPTCP cannot be used since the end devices are unable to deliver acknowledgments, the ATSSS-LL is the only one available for ATSC 3.0 and 5G convergence, which limits the ATSSS operations to only Traffic Steering. In order to further overcome the limitations listed in 3.3.1, an additional delivery mode, more flexible than MPTCP, would enable the modes of Traffic Switching and Splitting between broadcast and mobile networks. 3GPP introduced Release 17 ATSSS enhancements includes the incorporation of QUIC [93] as an ATSSS delivery mode. QUIC protocol provides a lightweight and low-latency connection establishment, compared to TCP, but it is implemented to run over UDP connections.

To further overcome limitations 1), 2), and 6); it is proposed that the convergent architecture incorporates QUIC functionalities as the protocol used in the ATSSS procedures, effectively turning this solution into Layer 4 Convergence. QUIC provides a simple framework to operate with several access networks by including the concept of Connections and Streams. The ATSSS UPF incorporates the QUIC Server, while the device consuming the convergent service features the QUIC Client. To support both the 5G Network and the ATSC 3.0 Network, two different QUIC profiles are deployed: the baseline or QUICv1, which will be radiated over the 5G RAN; and a Multicast QUIC one, with packets being broadcasted by the ATSC 3.0 Network. This multicast extension of QUIC is being standardized at present time [94] and it targets the mass unidirectional delivery of information, adding new packet and frame formats, and disabling anything related to encryption or frame reception acknowledgements. Note that 3GPP is not considering including multicast QUIC profile into ATSSS Release 17 functionalities. Each ATSSS service in the QUIC connection have their own Connection ID (CxID) but different IP pairings for each access network used i.e. one pairing for the ATSC connectivity and other one for the 5G one. This allows the QUIC Client in the device to easily switch or steer the multimedia flow between access networks, depending on the instruc-

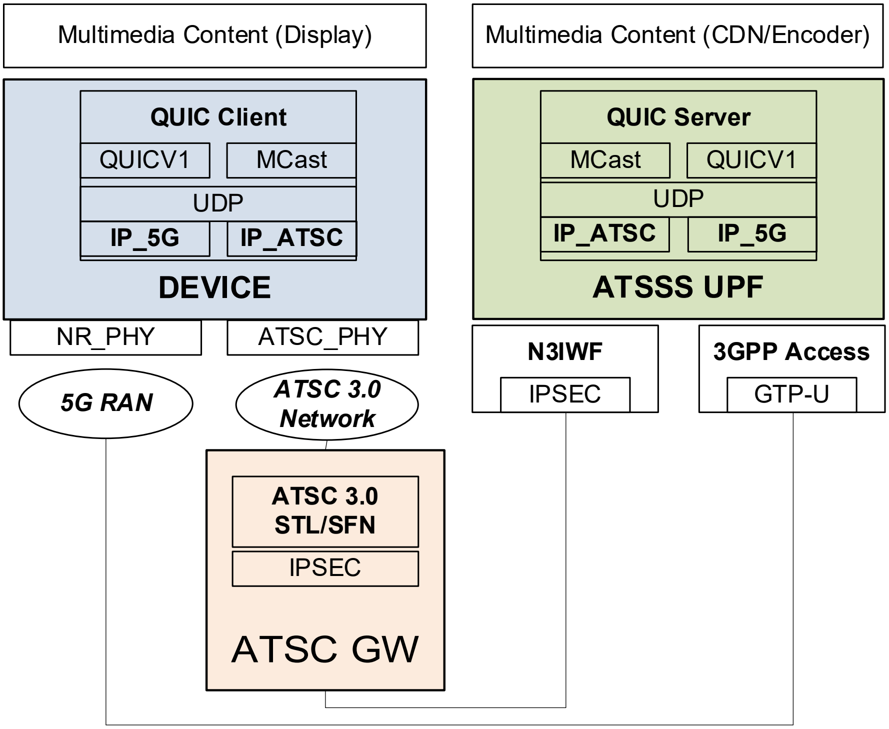


Figure 3.7: Deployment of ATSSS using QUIC for Convergent Services over ATSC and 5G Networks.

tions sent by the 5G Core Network. However, Traffic Splitting is not supported with the current configuration as it requires the multipath QUIC profile [95]. Figure 3.7 describes the relevant protocol stack of the solution, when applying QUIC delivery mode into the Untrusted Convergence scenario.

3.4.1 Convergent Service Call-flows

To showcase the potential capabilities of the QUIC-enabled Convergent Core, two Convergent Services have been selected to be analysed: File Repair and Video Offloading. These services do not require of Traffic Splitting, as it cannot be supported with the proposed QUIC core. Ilustrative call-flows are included, to describe the interaction between the 5GC, the ATSC 3.0 Gateway, and the dual receiver and QUIC-enabled device.

For Video Offloading, devices solicit content from the Data Network or Content Delivery Network via 5G and notify their ATSSS and QUIC capabilities to the 5GC (1). The 5GC then creates the QUICV1 path between the ATSSS UPF (QUIC Server) and the device (QUIC client). As part of this procedure and if the devices support ATSC 3.0 connectivity, the listener for the QUIC multicast path is created, with the configuration to setup this connection coming from the 5GC (2). As the content gets popular (e.g. a live sports event, viral content), and the conditions are met (e.g. the devices are geographically close to be served by one ATSC 3.0 GW) the 5GC decides to offload the content and deliver it using the ATSC 3.0 infrastructure to the compatible devices, notifying the ATSC 3.0 5G AF to provision resources (3), and encapsulated with the QUIC multicast headers. Note that the content could carry this information in their file descriptor manifest, in the method described in [72]. The ATSSS UPF sends a notification to each QUIC client at device side, waking up the Multicast listener and the related lower layer modules such as the ATSC 3.0 Physical Layer (4). Then, the multimedia content is routed through the N3IWF and forwarded towards the ATSC 3.0 GW (5), which ultimately will broadcast the content in the ATSC 3.0 network (6). From the device side, this decision is transparent and totally carried by the QUIC client, which removes the multicast headers and sends the multimedia data towards the device display. Finally, as the content decreases in popularity, the QUICV1 5G access is re-enabled using standard paging procedures and the multicast listener is deactivated, ending the Convergent Service. Regarding File Repair, it is the service where an erroneously decoded or not received portion of the broadcast stream gets retransmitted over unicast networks and reassembled before being displayed, avoiding the pixelation or degradation in quality caused by the outage. While this problem is easy to solve at Application Layer by retransmitting DASH segments, the use of low level solutions such as QUIC allows this process to be totally agnostic to the display application as it is the QUIC client which is performing the correction Layer 4 level. In detail and shown in 3.9: before the multimedia content delivery begins, it is assumed that ATSC 3.0 Network and the 5G Core Network have been interconnected with all the related message exchange, including the setup of the IPsec tunnel between the ATSC 3.0 GW and the 5GC N3IWF (1). After the interconnection is done, the ATSC 3.0 GW activates the QUIC multicast server (2), that will encapsulate the multimedia data to be broadcasted over the ATSC 3.0 Network. In an undetermined point in the future, a dual 5G-ATSC 3.0 device attaches into the 5GC, signals its QUIC and ATSSS capabilities (3). Then, the device activates its own QUIC client and display application, effectively tuning into an ATSC 3.0 service, which is delivering the service over broadcasted QUIC multicast packets. The device will use the 5G connection to periodically report back

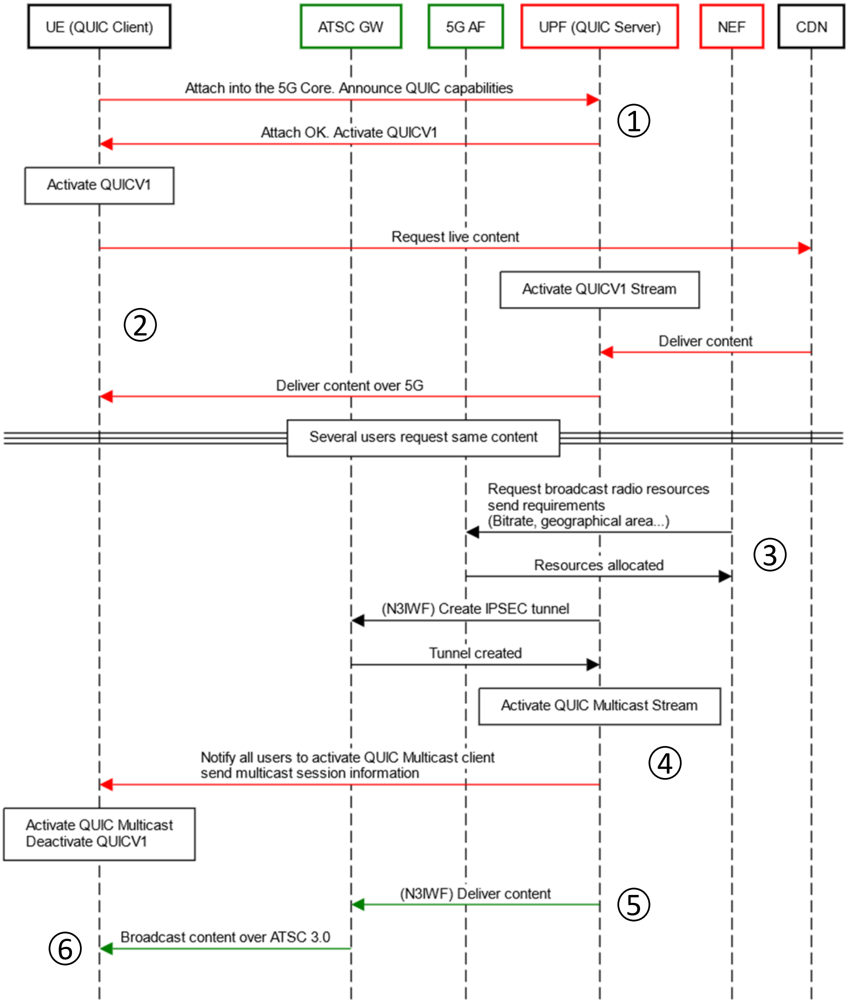


Figure 3.8: File repair call-flow using ATSSS and QUIC. The Attach and internal 5G messages have been simplified, as they involve additional network functions besides the UPF.

via 5G the ACKs belonging to the multicast transmission to the ATSSS UPF (4). In the event of a broadcast delivery failure, the QUIC Server in the UPF will notice since the ACKs of the packets received will be in the wrong order (5). The ATSSS UPF launches a request for the correct QUIC packet range to the ATSC 3.0 GW using the N3IWF, and receives a response (6). Then the

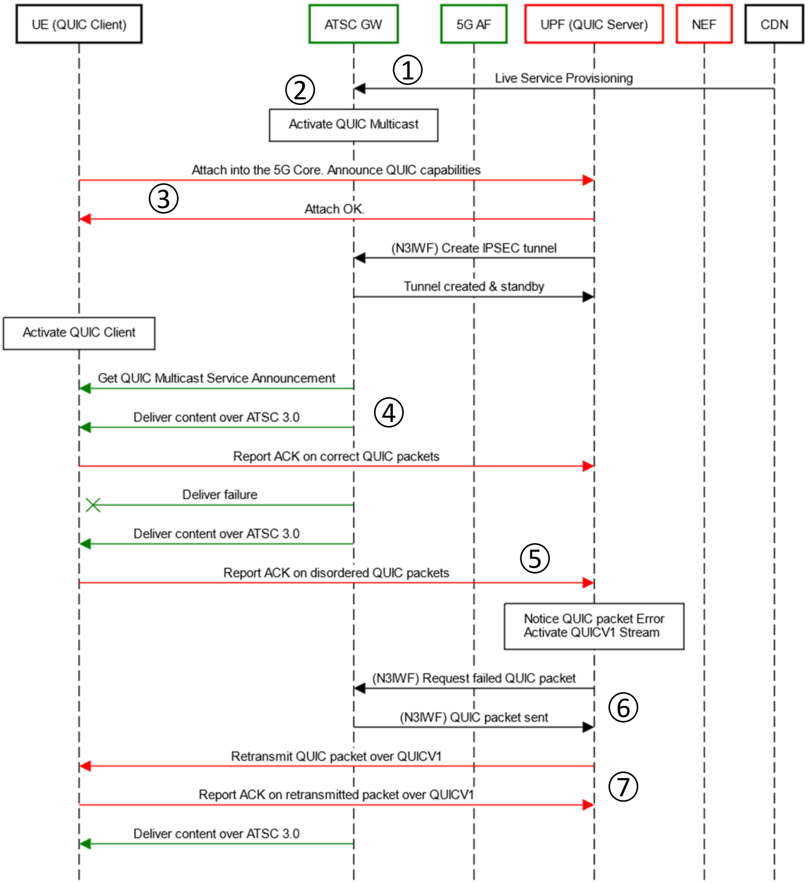


Figure 3.9: File repair call-flow using ATSSS and QUIC. The Attach and internal 5G messages have been simplified, as they involve additional network functions besides the UPF.

UPF delivers this data over the 5G Network using the same QUIC Connection parameters as the multicast ones, so the QUIC client in the device can use it to restore the data stream (7). The device keeps getting the content over broadcast as usual, until the user decide to turn off the display and shut off the QUIC client.

Chapter 4

Release 17 Mobile Broadcasting & Evaluation

This chapters covers the topic of Point-to-Multipoint capabilities in the 5G System (5GS) natively. The main difference with the contents of 2 is that the so called 5G Broadcast relies on LTE architecture and components, while 5G Multicast/Broadcast Services or 5MBS is fully integrated into 5G and its Network Functions. The chapter is structured as follows: First, an introduction of how 5MBS was analysed, research and standardized inside Third Generation Partnership Project (3GPP) is provided, alongside a high-level description of 5MBS; which is followed by a laboratory, components and testing framework description to evaluate the performance of this multicast technology. The chapter continues with a characterization of the 5MBS prototype developed by the author as part of the Mobile Communications Group (MCG) Core team; explaining the implemented features and motivation behind the implementation decisions. Chapter 4 closes with a performance study of the 5MBS prototype and a discussion of the results obtained.

4.1 Point-to-Multipoint Standardization in Rel-17

The necessity to include PtM[1] in 5G was identified very early in the Rel-15 standardization period. In [96], broadcast and multicast functionality is listed

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[1] In this Chapter, Point-to-Multipoint or PtM is used as reference to Multicast and Broadcast communications

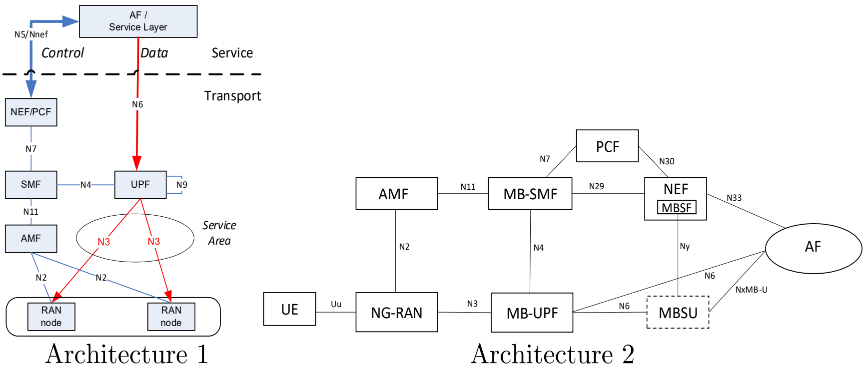


Figure 4.1: Proposed architectures for the Multicast-Broadcast 5G extension. From left to right: Architecture 1, based on modifications of the unicast 5G Core (5GC), Architecture 2, with dedicated NFs to enable Multicast-Broadcast transmissions

as a requirement for the 5GS. However, due to time constraints it was not considered until Rel-17. The initial effort to include Point-to-Multipoint capabilities in the 5G System began in 2019 and the term "5G Multicast/Broadcast Services" or 5MBS was adopted. 3GPP allocated resources to analyze what existing standard modifications were needed to support Multicast and Broadcast communications in 5G. This effort was spearheaded by SA2 Working Group, in the form of an Study Item (SI) called "Study on architectural enhancements for 5G Multicast-Broadcast Services", for the transport and core aspects. On the radio side, RAN2 Working Group (WG) was also involved, with the notable exclusion of the Physical Layer WG or RAN1 since of the design goals of 5MBS was to avoid modifications of the NR waveform to ease adoption among manufacturers [97]. The targeted verticals for this SI are Transparent IPV4/IPV6 multicast delivery, V2X, Public Safety, IPTV and IoT use cases. It is noteworthy to highlight the absence of Terrestrial Broadcast or DTT in the targeted verticals, as the 3GPP partners argue that it is already covered by LTE-based eMBMS. The 3GPP research work finished in March 2020, with the reached conclusions of the preliminary study reflected in TR 23.757 [98]. In this document, the 3GPP consortium provided the requirements of the system, including the mandate to be a fully 5G-based system that used NR as the Radio Access Technology (RAT); and as previously mentioned, to avoid changes in the NR physical radio parameters. 3GPP derived 8 Key Issues that the 5MBS should solve or include as functionalities. These Key Issues were classified and disseminated to interested 3GPP members to gather solutions. In detail, the 8 Key Issues are:

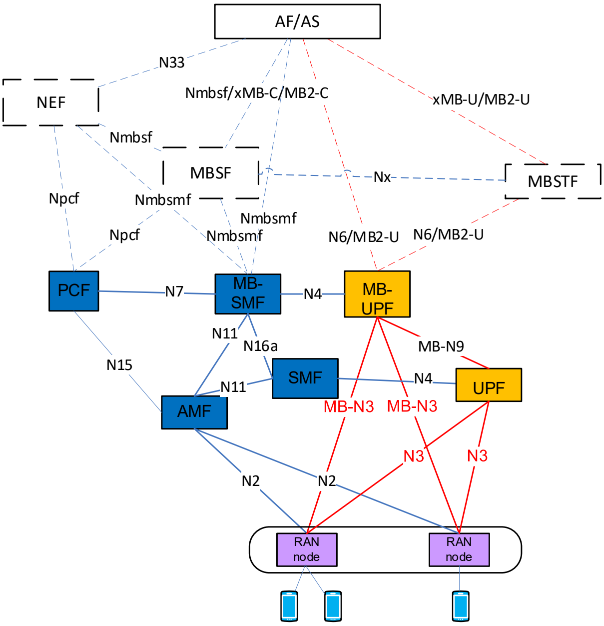


Figure 4.2: Final proposed architectures for the Multicast-Broadcast 5G extension. Architecture 3, which took parts from Architecture 1 and Architecture 2 to create a combined solution

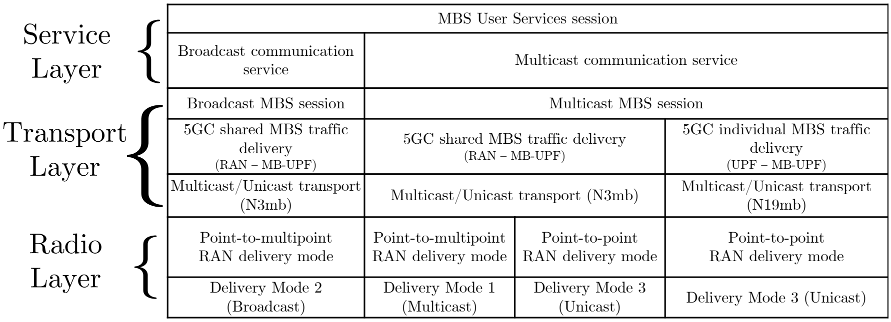
- Key Issue #1: How to perform the session management in 5G Multicast/Broadcast
- Key Issue #2: How to define the Service Levels to properly address the targeted services
- Key Issue #3: How to support different levels of authorization in Multicast transmissions
- Key Issue #4: How to provide Quality of Service to Multicast/Broadcast
- Key Issue #5: How to enable Broadcast TV Video and Radio services
- Key Issue #6: How to commission local Multicast/Broadcast Services
- Key Issue #7: How to perform reliable switching between unicast and multicast
- Key Issue #8: How to achieve reliable switching between unicast and broadcast

However, Key Issue #5 and #8 where not included as part of Rel-17 and there are no plans to revise them in Rel-18 [99] since they fall out of the initial scope. On top of the aforementioned Key Issues, 3GPP proponents did also provide architectural reference solutions to enable Point-to-Multipoint communications. [98] included two different Multicast/Broadcast architecture propositions. They can be seen in 4.1. The final consensus among 3GPP partners was to converge both into a single one, which was the chosen architecture for Multicast/Broadcast Services; shown in Figure 4.2:

The result of the SI was a target architecture, solutions to solve aforementioned Key Issues and the required steps to incorporate multicast functionalities inside the 5GC. Additionally, several Work Item (WI)s were derived to address different verticals and open issues for the 5MBS functionality, such as the radio aspects of 5MBS [97] and security concerns among others [100] [101].

4.1.1 5G Multicast Broadcast Services

5MBS is a comprehensive framework, covering the Radio, Transport and Service Layer with its enhancements [102]. The technology consists of several additional functionalities; extensions to existing NFs and new ones, logical communication modes, types of transport, sessions, delivery modes, protocols, interfaces, and three different type of RAN communications. 4.3 shows the overall reference model that 5MBS uses. One of the most notable innovation of 5MBS is the reincorporation of multicast group communication capabilities, introduced in the 3G version (MBMS) but abandoned in the 4G version (eMBMS). This enables point-to-multipoint communication between a specific set of UEs, who must join the multicast communication. On the other hand, broadcast communications are permanently transmitted under a cell and any device



<table>
<tr><td rowspan="2">Service Layer</td><td colspan="4">MBS User Services session</td></tr>
<tr><td>Broadcast communication service</td><td colspan="3">Multicast communication service</td></tr>
<tr><td rowspan="3">Transport Layer</td><td>Broadcast MBS session</td><td colspan="3">Multicast MBS session</td></tr>
<tr><td>5GC shared MBS traffic delivery
(RAN – MB-UPF)</td><td colspan="2">5GC shared MBS traffic delivery
(RAN – MB-UPF)</td><td>5GC individual MBS traffic delivery
(UPF – MB-UPF)</td></tr>
<tr><td>Multicast/Unicast transport (N3mb)</td><td colspan="2">Multicast/Unicast transport (N3mb)</td><td>Multicast/Unicast transport (N19mb)</td></tr>
<tr><td rowspan="2">Radio Layer</td><td>Point-to-multipoint RAN delivery mode</td><td>Point-to-multipoint RAN delivery mode</td><td>Point-to-point RAN delivery mode</td><td>Point-to-point RAN delivery mode</td></tr>
<tr><td>Delivery Mode 2 (Broadcast)</td><td>Delivery Mode 1 (Multicast)</td><td>Delivery Mode 3 (Unicast)</td><td>Delivery Mode 3 (Unicast)</td></tr>
</table>

Figure 4.3: Reference model for the 5MBS communication mode and its possible combinations.

Table 4.1: Standard specifications containing info for 5MBS

Layer	Description	TS Name and Reference
Service	5MBS Details regarding the MBS User Services Sessions, the integration within 5MBS and the possible ways to provision content	5MBS User Service Architecture [103] 5MBS User Service Protocols [104]
Transport	Description of the Multicast Sessions and Broadcast Sessions, the role of the NFs and the procedures in the 5GC	5MBS Core Enhancements [105]
Radio	Enhancements at the NG-RAN and RRC and to support 5MBS	NG-RAN details [106] 5G RRC procedures [107]

in coverage can tune and receive the broadcast content. Multicast transmissions can be transparently delivered to the devices, this means that the UEs reuse the unicast procedures to get the content and are not necessarily aware that the content is being multicast. More details regarding the different communication modes can be found below. The technical information detailing 5MBS inside 3GPP is spread across several documents, with table 4.1 containing a summary.

5MBS Communication Modes

5MBS is composed of three different type of communications: Broadcast, Multicast and Unicast. Each one of them fulfils vertical service requirements and it is tailored towards specific scenarios. Choosing a type of communication will determine several aspects such as the Delivery Mode used, Transport type, MBS Session details and other related parameters. A more detailed explanation for each type of communication can be found next:

- **Broadcast** communications in 5MBS allows for PtM transmissions to devices which are in RRC states either CONNECTED, IDLE or INACTIVE with the network. This implies that devices who may not be attached in the network are capable of accessing the Broadcast transmission, provided that the content is not encrypted and the devices have the Electronic Programme Guide (EPG) to locate the service inside the content i.e. a priori information of how to locate the service or an initial download of the stream manifest. Broadcast services are characterized by being fixed, albeit suboptimal QoS, since they are planned to be received by users at the edge of the cell, and lost packets will not be retransmitted. In other words, users who receive a better signal quality are not adapting their channel to the capable bandwidth. Finally, while 5MBS has not define guidelines in regards to SFN operation, implementation specific solutions are possible as long as they are transparent to the end-device.

- **Multicast** communications in 5MBS are focused towards providing a reliable and high QoS to a group of users who have registered and are authorized by the network. Multicast includes several features to ensure the transmission quality. In order to do so, the multicast users should be in the RRC_CONNECTED state. Devices belonging to the Multicast group are capable to report back their air channel status condition so the gNB can adapt the channel to ensure the QoS of the users; or in extreme cases, derive poor coverage users into Unicast until their reception quality improves. Additionally, the Multicast communication can be configured to retransmit lost physical layer packets using the Hybrid Automatic Repeat Request (HARQ) scheme. Service continuity is supported via lossless handover. In the case that a moving device enters a gNB that does not support 5MBS, it will be transferred into Unicast.

- **Unicast** is also included as part of 5MBS. It inherits all the standard Fifth Generation Mobile Network (5G) NR functionality, and it is a fallback communication to ensure the service continuity in Multicast sessions and in the case that some gNBs involve in the Multicast session do not support 5MBS. Unicast support also enables the ability for 5GS to derive users consuming popular content into a temporal and more efficient multicast one, in order to save resources. This is known in Fourth Generation Mobile Network (4G) as MooD.

5MBS MBS Sessions

Broadcast/Multicast MBS session form the first layer of the Transport Layer stratum. It inherits several concepts and identifiers from 4G eMBMS, such as Service Area and TMGI; while leveraging new innovations like the integration with 5G Media Streaming (5GMS) framework in the Service Layer and the reuse of 5G QoS models (5QI) for 5MBS data flows. Two different types of MBS sessions are specified: Multicast MBS Session and Broadcast MBS Session and are created with a scheduled interval, that is, they are provisioned for a time period. When the timer expires, the MBS Sessions are destroyed. Multicast MBS Sessions have a more complex life-cycle compared to Broadcast MBS

Sessions, as Multicast MBS Sessions are more dynamic and could be stopped unexpectedly based on UEs activity e.g. all UEs involved in the Multicast group drop the Multicast communication.

The set of parameters characterizing the context for Broadcast and Multicast sessions is different, composed of both mandatory and optional parameters. Variables common to both include i) TMGI, uniquely defined per MBS Session; ii) QoS information defining the quality profile of the MBS flows; iii) TEID for data distribution, identifying the GTP multicast tunnel ID used in delivering data towards the NG-RAN; iv) related 5GC info of what NFs are used in the MBS transmission, such as AMF, MB-SMF and PCF; v) a list of NG-RAN gNBs, stored at AMF, that define the geographical area of the MBS transmission; and vi) Area Session Identifier, which when used alongside the TMGI identifies localized or regional content delivered in a given area.

Going over the specifics for Multicast MBS Sessions, the mode-specific parameters included are: i) A pair of multicast IP addresses (source and destination) which can be used instead of the TMGI; ii) the list of devices that are accessing the Multicast data; iii) the Multicast session state, detailed in Figure 4.3-2 of [105]; iv) MBS Service Area where the content can be radiated, in the form of Cell IDs or Tracking Area Identity (note that the AMF will translate this into a list of Node IDs); and v) a fallback unicast IP address and TEID for Individual Delivery. Broadcast MBS Session context has these particular variables on top of the common ones: i) the mandatory MBS Service Area, in the form of a Cell IDs or set of Tracking Area Identities, that define the geographical area of the broadcast data delivery; and ii) the MBS Frequency Selection Area ID [2], to aid interested UEs to sync into the Broadcast MBS radio transmission.

5MBS Delivery Modes

To accommodate both broadcast and multicast communications (and unicast as back-up), keep service continuity and 5G backwards compatibility, 5MBS introduces 4 different delivery modes, two between the NG-RAN and the UEs, and two between the 5GC and the NG-RAN. These delivery modes have been designed for different scenarios and backwards compatibility, such as type of 5MBS Communication Service, the UEs location and radio channel quality received, and many other parameters. In the 5GC, the two delivery modes between the MB-UPF(or UPF) and the NG-RAN are the 5GC Individual De-

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[2] MBS Frequency Selection Area ID or MBS FSA ID is a parameter, preconfigured in the NG-RAN nodes, that define which frequency ranges and cells are used for the broadcast transmission. The UEs interested in broadcast content will compare the radio signalling info against its stored from the service announcement to discern and tune to the desired broadcast service.

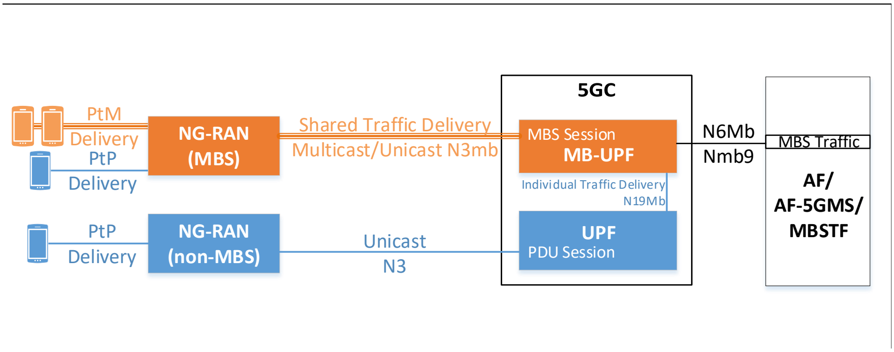


Figure 4.4: The different delivery modes introduced in Release 17 5MBS. The MBS data ingest point may be an AF, a 5G Media Streaming enabled AF, or the MBSTF.

livery and the 5GC Shared Delivery. On the one hand, 5GC Individual Delivery is defined as the delivery between MB-UPF and UPF, connected by the new N19mb interface (either unicast or multicast), and is used to keep the multicast service on-going when a UE performs handover from a 5MBS capable gNB into a 5MBS non-capable gNB. It is important to note that 5GC Individual Delivery is associated with an 5MBS service and should not be used for traditional unicast delivery, unless that communication has point-to-multipoint features. On the other hand, 5GC Shared Delivery implements a pipe from the MB-UPF towards the MBS capable NG-RAN, using the new interface N3mb (either unicast or multicast), which will then be radiated using PtM physical channels (1st RAN Delivery Mode) or unicast ones (2nd RAN Delivery Mode). By 3GPP guidelines, Broadcast Communication Mode should only use 5GC Shared Delivery. Figure 4.4 shows the relationship between the different terms.

5MBS Network Functions

To support Multicast/Broadcast communications, new additions and modifications of existing Network Functions are added into the 5G Core architecture. The 5MBS Delivery Modes where devised to interact with legacy equipment and allow for a gradual deployment since they support unicast transport and communications until the underlying infrastructure is capable to hold multicast communications. This translates into a direct interaction of the new 5MBS related components with the legacy and Point-to-Point (PtP) based 5GC NFs to create Multicast/Broadcast services. Inside the transport layer, Multicast Broadcast UPF or MB-UPF and Multicast Broadcast SMF or MB-SMF complement the UPF and SMF respectively. At the Service Layer, optional network functions Multicast Broadcast Service Function (MBSF) and Multicast Broadcast Service Transport Function (MBSTF) provide the necessary application-level functionality to monitor, manage and anchor the MBS Communication Service(s) and provide the interworking support of 5MBS with LTE eMBMS. More info regarding MBSF and MBSTF can be found on [103]. Several 5GC components are also modified to support the 5MBS framework. The components modified and their functionality are detailed next:

- **MB-SMF** provides session management and control of MBS Communication parameters, including choosing of an QoS profile for a MBS Data flow or retrieving it from the PCF, and performs the control data provision for the MBS data tunneling (between the MB-UPF and NG-RAN) based on those rules. The component is also tasked with the assignment and release of TMGIs for MBS Sessions; and handles the UE procedures of join/leave in Multicast transmissions. The MB-SMF also has specific functionality based on the 5MBS Communication Mode used: For Broadcast Communication Mode, the MB-SMF also contacts the NG-RAN via AMF petitions to manage the on-going control data of a Broadcast session. In the case of Multicast session, the MB-SMF interacts with the NG-RAN to establish user plane flows between the MB-UPF and RAN nodes,be it over Shared or Individual Traffic Delivery; and provides SMF with the MBS Session context in the case of Individual Traffic Delivery.

- **MB-UPF** applies Packet Detection Rule (PDR) for downlink 5MBS traffic packets based on the 5MBS Delivery Mode used i.e. creating the tunnels towards the NG-RAN via N3mb in 5GC Shared Delivery or forwarding data in a PtP manner to each UPF involved in the MBS transmission via N19mb for 5GC Individual Delivery. Also, it enforces QoS on the MBS Session packets, based on existing unicast means; based on the commands of the MB-SMF received over the N4mb interface. 3GPP allows for the MB-UPF to be colocated alongside the UPF.

- MBSF provisions the application level state and signaling to the MBS Sessions and the underlying 5G Core. It can launch sessions according to the 5GMS framework rules over trusted and 3rd party domains, assigning and managing the TMGIs. When launching a MBMS Session, it will also provide the necessary information to the MBSTF, such as the MBS Distribution method used.

- MBSTF prepares and delivers the data from the AF or CDN to the MB-UPF. It can apply additional functionalities such as the incorporation of manifest data, AL-FEC encoding, creation of object based delivery via FLUTE, or transparently deliver the data to the MB-UPF.

- AMF is extended to support the signalling exchange between the MBS-capable NG-RAN and the MB-SMF for MBS Session management. The AMF is the entity aware of which parts of the NG-RAN is capable of MBS, and informs the MB-SMF/SMF of which delivery mode to use. This includes the paging for multicast session activation in case that the UEs are in IDLE state. Last, the AMF also translates the MBS Session Context info regarding the geographical area into a list of gNBs represented by cell IDs, for Broadcast MBS Sessions.

- PCF handles the Quality of Service for MBS Sessions, providing this information to MB-SMF. The QoS profiles definition can be updated from trusted AFs, or from untrusted AFs via NEF. The MBS Service Layer component, the MBSF, also has access to PCF policies.

- UPF interacts with the SMF to create a tunnel for MB-UPF multicast data forward it to UEs via unicast PDU Sessions in the 5GC Individual MBS traffic delivery method.

- SMF can be deployed as part of the MB-SMF or not; and it is involved only in Multicast MBS Sessions, where it executes these functions: i) Discovering the available MB-SMF; ii) act as a first checkpoint for UEs to join Multicast groups, where the SMF will retrieve the MBS subscription data and check if an UE is authorized to partake in the Multicast group; iii) modify the Session Context information based on MB-SMF data and modifying the UE Session Context into a the MBS one; and iv) setting up the MBS traffic transport between the non-MBS capable NG-RAN and the associated UPF.

- UDM contains information regarding if an UE is able to access Multicast MBS Sessions and which MBS Session IDs is it allowed to join. It is based on the Subscription Permanent Identifier (SUPI) Data Key. Note that some Multicast MBS Sessions may not be restricted allowing every UE under a geographical area to join.

- Unified Data Repository (UDR) may store UDM MBS subscription data detailed above for inactive users, which the UDM can request on demand when necessary. A trusted AF could modify this data (or be exposed via NEF), allowing for external entities or verticals to customize the authorized Multicast UEs dynamically.

- NRF is extended to host the new MB-SMF profile, with the MBS Session context info stored and exposed for other SBAs NFs. The NRF provides discovery of MB-SMF based on the MBS Session ID when requested by the SMF, for Multicast MBS Sessions. The discovery of the suitable AMF is done via the TAI list which is part of the MBS Service Area in Broadcast MBS Sessions context.

5MBS Deployment Options

One of the design goals of 5MBS was to separate the Transport Layer functionality from the Service Layer one. This was not the case in eMBMS, where the BM-SC was a mandatory component and performed Service Layer aspects such as content recoding and Service Announcement. In 5MBS, the deployment of the Service Layer specific components, i.e. MBSTF and MBSF is optional. Even if these components are deployed, it is flexible to colocate them with existing 5GC components or connect them via new interfaces. In the case that interworking with eMBMS and reuse of the xMB interface is wanted, MBSTF and MBSF provision is needed. In detail, 3GPP provides three different deployment options as seen in Figure 4.5. Each of the deployment configuration have available a set of features, provided the components (or their absence), and interfaces connecting them. Going thoroughly each deployment alternative: Configuration 1 does not have any of the new 5MBS Service Layer components, that is, MBSTF or MBSF. It is only used for Transparent Multicast or Transport Only Mode. This means that the MBS traffic will be delivered as it is to the Broadcast or Multicast session. In this case, the origin point for the MBS Traffic, the AF, will either interface with the NEF via N33 if it is untrusted, or directly provide the configuration parameters to the MB-SMF using N30 for the Reference Point 5GC or N29mb for the SBA 5GC. It is expected the AF

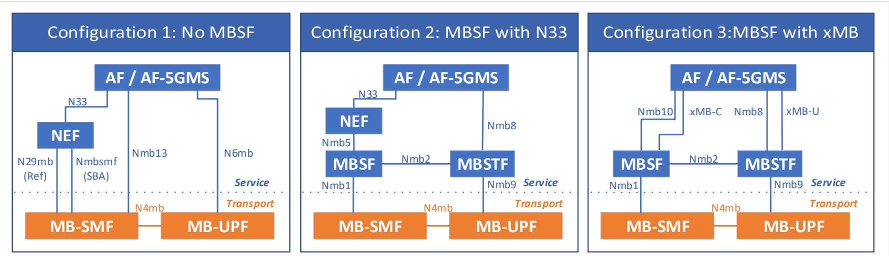


Figure 4.5: Different deployment options and interconnections for the 5MBS Service Layer and Transport Layer. Service Layer components in 5MBS have been made optional. Several lines connecting two boxes mean different interfacing options. Based on Annex A of [105].

to provide the 5GC the following parameters: Desired QoS, geographical area, list of authorized UEs (for Multicast) and a MBS FSA ID (For Broadcast). For the User Plane, the AF will deliver MBS Traffic over N6Mb to the MB-UPF and then forwarded to the NG-RAN.Configuration 2 contains the MBSTF and MBSF. The 5MBS is able to provide its Service Layer capabilities, allowing the transcoding of MBS data, addition of Forward Error Correction (FEC) or interworking with eMBMS. In this type of deployment, the AF will always interface with the NEF to expose MBSF capabilities over N33. Note that the MBSF can be colocated with the NEF and the AF, if the AF is trusted. The MBSTF is used as the entry point for MBS Traffic, via Nmb8, will be delivered to the MB-UPF and then reach the NG-RAN. Transport Only Mode is also available even if the MBSTF and MBSF are deployed. Configuration 3 is a variation of Configuration 2. In this case, the MBSTF and MBSF implement the legacy eMBMS interface xMB to provide Service Layer features to the MBS Session. Instead of using N33 and Nmb8 to deliver data, xMB-C and xMB-U are used respectively for the Control and User Plane; bypassing the NEF. This facilitates the interworking with existing LTE eMBMS infrastructure, for example used in Public Warning Services.

TS 23.247[105] contains more 5MBS information that the one included in this thesis section. It was deemed not suitable for the high-level overview of this part. Nevertheless, a summary of the contents of TS 23.247 is described next: Regarding functionalities, including the support of Multicast UE authorization, QoS enforcement, local content delivery, use of eMBMS for public warning, security in MBS and Service Announcement can be found in chapter 6 of [105]. Chapter 7 includes detailed call-flows specifying the message exchange between different NFs for MBS Session Management; Multicast Session join and leave, mobility; and MBS Location dependent service provision. The protocol stack detailing the layering of MBS communications is located in [105] chapter 8. Last, the SBAs MBS services is detailed in chapter 9; including which NFs is involved, type of service, inputs and outputs required and optional.

4.2 Laboratory Description

The proposed framework for the 5MBS evaluation has been carried out in UPV premises, as part of the Mobile Communication Group Open 5GC Lab. The Mobile Communication Group has provided a network of laboratories for Information and Communication Technology (ICT)-based experiments in several verticals, which the Open 5GC Lab forms part of. These laboratories are comprised of a plethora of equipment, including special hardware, both for high-performant networking and 5G specific components (including radio and core). Several software products are also included, ranging from open-source developed tools, suites, and commercial ones. This equipment has been used to obtain Chapter 4 results. The following section contains a description of the infrastructure at 2022, including details of the most relevant components, current 5G capabilities and other equipment.

4.2.1 VLC 5G Campus

VLC Campus 5G [108] is an experimental centre located at UPV Valencia Campus for testing innovative 5G services and applications for industry verticals, using both commercial and open-source 5G equipment. It has been funded by European ERDF initiatives [109] over several rounds of financing. It consists of a combination of outdoor and indoor 5G nodes to address different objectives. The outdoor nodes, are equipped with Nokia equipment [110] and are focused on novel 5G devices prototype evaluation in realistic environments. The campus nodes also provide services for education applications, allowing for direct interaction with university personnel and students. For example, multimedia feed from production cameras captured in the campus can be sent via 5G and allow for remote outdoor lessons inside the UPV campus. VLC Campus 5G is equipped both with NSA in the n258 millimetric Wave (mmW) (with 4G B7 as LTE anchor) and Stand-Alone (SA) in the B40 band.

As part of the same initiative, UPV has deployed several indoor nodes with the goal of providing more experimental laboratory for software solutions and suitable environments for 6G and beyond 5G applications. In detail, the Mobile Communications Group have provision the following 5G laboratories:

- An human-centric immersive communications supporting telepresence, haptics and holographic technologies to host future pilot 6G applications, called the Immersive Laboratory. The Immersive Laboratory is formed by 2 different sites, each equipped with specialized devices to enable holographic, telepresence and haptic, interconnected to each other, such that it is possible for bilateral communications between sites. The nodes target the eMBB and URLLC communications and are equipped with commercial equipment that support these modes. The laboratory is in the preliminary integration phase by the equipment suppliers.
- A real-life Industry 4.0 5G testbed with a distributed deployment, equipped with sensors, Automatic Guided Vehicles, and machinery. Part of it is located at Mobile Communication Group premises as an edge node, connected via a dedicated HL4 fiber connection provided by Telefonica to the Ford Motor Company's engine plant in Almussafes (Valencia) [111] featuring low latency and deterministic QoS. This edge node is also con-

nected to RedIRIS-NOVA, a 100 Gbps high-capacity optical network that connects the main academic and research centers in Spain, with possibilities to connect the edge node to GÉANT [112] to guarantee QoS across links between European sites.

- The Open 5GC laboratory. As part of the VLC 5G Campus, the MCG has provision a networking centric laboratory for integration of 5G equipment with several 5GCs and development of 5G Private Networks innovations. It allows for 5G RAN and NFs deployment based on virtualized resources over high-performance HW, that can emulate edge, distributed or containerized environments. The Open 5GC laboratory features software-based and licensed 5GCs: Rel-16 SA Cumucore [113], Fraunhofer FOKUS Open5GCore [114]; and Open Source 5GCs, such as OpenAirInterface [115], SRSRAN [116] and Free5GC [117]. Additional relevant software include the professional benchmarking tool Landslide [118], capable of simulating thousands of users and stress the 5GCs against several traffic models to derive and analyze metrics. The laboratory also has datacenter grade equipment, comprised by an SDN router [119] and two high-performance servers [120], as shown in Figure 4.6. The servers have been installed with a Proxmox Virtual Environment [121], which provisions Virtual Machines and VLANs to deploy experimental networks for 5G experiments.

Figure 4.6: The SuperServer 1029P-WTRT, which hosts several 5G Cores and Network Functions and is the foundation of the Open 5GC Laboratory

- A Software Defined Radio Laboratory, separated into two different parts: A high-performance computational cluster, with Graphic Processing Unit (GPU)s to simulate the performance of advanced wireless physical layer schemes; and a end-to-end software-based radio setup for 4G, 5G and

DTT technologies, in order to test new radio resource management techniques, new waveforms and numerologies and perform drive-test measurements. The main research line for the Software Defined Radio Laboratory is implementation of 5G Broadcast components and evaluate them as part of the 5G-MAG Reference Tools initiative [122]. The current equipment is comprised by B210 Universal Software Radio Peripheral (USRP)s [123], commercial PCs with the SDR drivers, and high-performance nodes optimized for parallel computing algorithms such as wireless performance studies.

4.2.2 Open5GCore

The evaluation of 5MBS has been carried out in the Open 5GC laboratory. The Open5GCore commercial software is a Linux-based testbed oriented product made for private networks and R&D initiatives. The current version, Release 7, features full compatibility with 5G Standalone deployments, including the necessary NFs to provide connectivity for the NG-RAN. Additionally, Open5GCore relies on a SBA-based implementation for the control plane signaling, following 3GPP guidelines. This means that the NFs forming the core will exchange HTTP/2 messages using an OpenAPI implementation. Open5GCore also allows for centralized deployments, with all 5G NFs in one machine, and distributed ones, based on VMs or Containerized Network Function (CNF)s. Lastly, the Open5GCore has available an benchmarking framework that emulates the NG-RAN, including gNBs and UEs. These emulated components are able of exchanging control and user plane traffic with the Core NFs. The emulated gNBs and UEs are also Linux-based and capable to derive metrics based on internal tools or execute OpenSource and Linux-based traffic performance measurement tools like *iperf* or *tcpdump*. The radio testing framework included in Open5GCore is known as the O5C Benchmarking Tool. A custom made low-level memory manager is implemented, that controls the memory usage of each NFs and dimensions it according to the process load.

As a research oriented product, Open5GCore has been featured in several papers and European R&D projects. In [124], the authors evaluate the performance of the Open5GCore in KVM-based deployment versus Docker-based deployment. [125] the use and evaluation of Machine Learning components in 5G Networks is evaluated using Open5GCore as benchmarking tool; while [126] details the problematic of roaming in 5G Non-Public Network (NPN)s, its possible solutions and how to extend Open5GCore to integrate them. Relevant research projects where Open5GCore is being used or extended include: FUDGE-5G [127], where Open5GCore is being extended to support the Interconnected NPNs Use Case; cross Asia-Europe project 5G!Pagoda [128], in

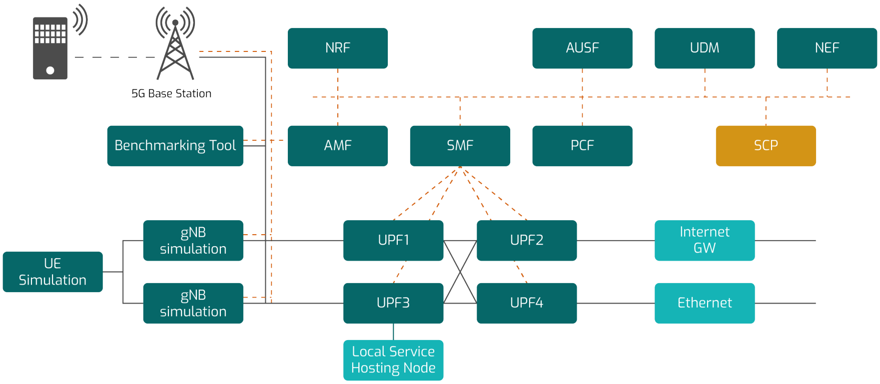


Figure 4.7: The current supported modes and Network Functions of the Open5GCore. The Open5GCore provides the NRF, AMF, SMF, PCF, AUSF, UDM, NEF, and UPF. It also features a Service Communication Proxy, acting as the control plane routing agent for 5G testbed interconnection and a gateway between different network domains.Extracted from [114]

which Open5GCore was used as the European Network Slice component; and 5G-VICTORI [129], a trial focused project where Open5GCore was used to deploy a 5G NPN in a rail communication service for passengers amenities.

4.2.3 Landslide

Landslide is a commercial tool developed by Spirent Communications, allowing for the execution of benchmarking trials for devices, network components and whole mobile systems, ranging from 3G tests up to 5G component testing. Mobile Network Operators or manufacturers can use Landslide to emulate parts of the network, both at control and user plane, in order to evaluate the correct functionality and the scalability behaviour versus different traffic profiles and volumes. For example, Landslide is able to test the capacity coursed through the 5G UPF and evaluate the percentage of lost, duplicate packets, the jitter and latency. For the Control Plane, a basic functionality test would include the attach procedure and the handover procedure. landslide defines the components to be tested as System under Test or SUT(s).The software is flexible enough to accommodate for complex network deployments, such the use of server proxies, Virtual Local Area Network (VLAN)s, node failures, diversity paths, and other corporate network techniques.

With its flexible licensing business model, the tool can be used by several types of users and not only for benchmarking of real deployments but also for research purposes. The system can be configured over dedicated hardware or deploy an special system image optimized for virtualized and generic purpose environments, where the user is granted greater flexibility in the allocated resources to the software. This has been chosen as the deployment alternative in the Open 5GC laboratory, where the same SuperMicro server both host the Open5GCore and the Landslide components. Landslide is composed of three subsystems that need to be deployed in order to use the software: Test Administration Server or TAS, Test Server or TS, and the Landslide Client. The functionality of each component is shown in figure 4.8 and detailed as follows:

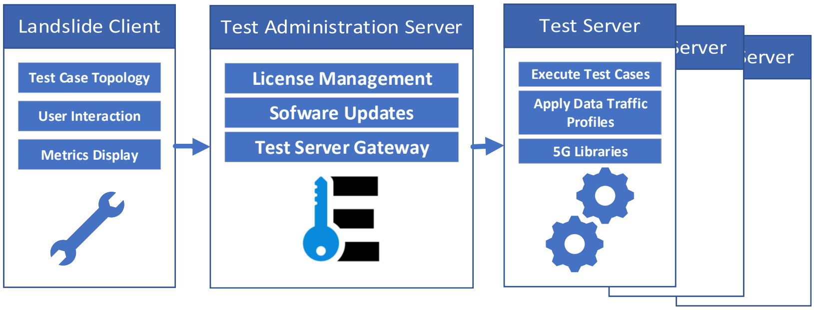


Figure 4.8: Interaction with Spirent Landslide Benchmarking Tool and its subsystems. The Landslide Client only interacts with the Test Administration Server, which manages and forwards the Test Case data to the Test Servers

- The TAS is the main element for the management of Landslide. It oversees the user account configuration, the system and licenses status, and the version update for each component. Also, it is where the user test profiles and available libraries emulating functionalities or components are stored. The TAS is also tasked with deriving metrics based on the test performed and presenting them in a spreadsheet to the user. Depending on the license purchased, TAS will allow a variable number of emulated users for stress benchmarking. This component directly interacts with one or several TS, depending on the licensing plan, and needs a management port to be established per TS. By using this management port TAS keeps track of the TS status, sends configuration commands, or notifies the user in case of failures. The users do not interact directly with the TAS, all the configuration and information delivery is done via the Landslide Client.
- The TS is the element that executes the benchmark trials, defined inside Landslide as "Test Cases". The TS contains the interconnection and net-

working logic behind the Test Cases, the implementation of the emulated components, the associated protocol stacks, and the data traffic profiles to be used in the Test Cases. Inside of the TS, there is are port interfaces (which can be either physical or virtual, depending on the deployment), for the connection with the TAS and the communication with the SUTs. For the emulated devices and components, the TS allocates a port in the range of the loopback internal network i.e the 127.0.0.0/8 IP range. The TS is also capable to connect with other deployed TS to create dependency between different Test Cases e.g. execute Test Case 2 on TS instance 2 if TS 1 Test Case 1 fails.

- Landslide Client is the desktop application that the user interacts with in order to create Test Cases and manage Landslide configuration. It is a Java-based Graphical User Interface (GUI) where the test sessions are assembled, including the type of test to be performed. The GUI will also show the real-time metrics derived depending on the type of test, and add automatization steps depending on conditions in the running Test Cases e.g Execute Test Case 2 when Test Case 1 finishes successfully. Note that the Client interacts with the TAS and does not access the TS(s) directly.

4.3 5MBS Prototype

This section is focused on the prototype, first explaining the design goals and where does it fit in the overall 5MBS framework. Then, the implementation is presented, detailing the modifications performed to the baseline 5G NFs. In an agreement between the MCG and Fraunhofer FOKUS, the source code of the Open5GCore is available to be enhanced by the Open 5GC laboratory personnel. A prototype to test basic functionalities of 5MBS has been developed over extensions to the 5G baseline architecture, that is, the mandatory NFs required to perform unicast communications (UPF and SMF). In detail, the prototype has been based on the Open5GCore Release 7 software code.

4.3.1 Prototype Description

3GPP Release 17 included 5MBS as a new feature. As such, the time-to-market of commercial solutions by the manufacturers is not expected during the short term and some of them may even decide to not support the functionality in their components. Hence, in order to carry research and evaluation of point-to-multipoint in 5G, the MCG decided to create a new research line: to develop an extensible 5MBS prototype that will enable new studies, not only limited to multimedia applications, but also other verticals such as public warning or IoT. Other type of applications that the prototype could enable is LAN-type communications inside the 5GC for Industry 4.0 [130] . The goal of the prototype is to have a functional point-to-multipoint delivery inside the 5GC, in parallel with the standardization process of 5MBS.

5MBS is a complete solution that extends the 5GS functionality across all layers, as such, it provides modifications and extensions to components, interfaces, delivery modes, among many other concepts; as portrayed in 4.3. Standardized modes in 5MBS include, as an example, the interworking of 4G eMBMS, where the 5GC provides the Service Layer aspects and connects to the eMBMS BM-SC. While in 4G eMBMS, the Service Layer and Transport Layer for Broadcast were bundled together, in 5G, the Service Layer components are not mandatory in order to support point-to-multipoint communications. In essence, the Transport Layer 5MBS components can operate on their own to provide Multicast in the mode known as Transparent Multicast [105], where the devices are not aware that the content they are consuming is being delivered using point-to-multipoint and the content is not transcoded. Transparent Multicast is the main functionality chosen to be supported in the prototype, as it does not require any additional procedures at Radio and Device Layer in order to test the delivery mode. It was chosen for the current version of the prototype to only implement Transport Layer functionalities, which means that the interworking with previous standards will not be supported, since the required components to do so are Service Layer related. Figure 4.9 shows the technologies that form the 5MBS Prototype. To enable Transparent Multicast, the baseline 5G components NEF, UPF and SMF, alongside the N3 interface, were extended. The SMF was expanded into the MB-SMF, and are co-located in the prototype. The MB-SMF is tasked with the exposure of multicast ser-

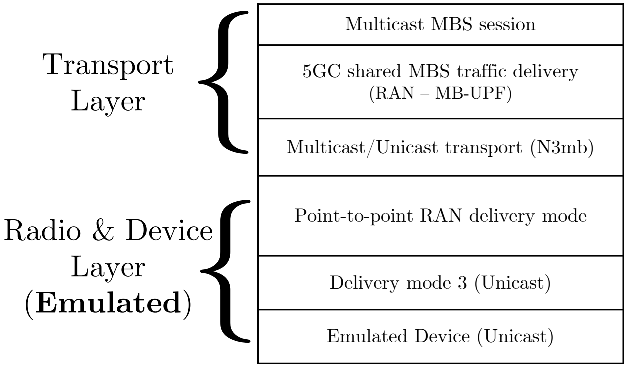


Figure 4.9: Concept stack of the MCG 5MBS prototype, with the modes supported

vices through the Service Based Interface (SBI) to other NFs. In a similar way, the UPF became the MB-UPF, both being co-located as the same component. The MB-UPF manages the multicast tunnels to the gNBs through the extended N3 interface or N3mb. NEF was also modified, to enable non-trusted application function (AF) access to the MB-SMF, providing the means to launch and terminate 5MBS sessions using 3GPP compliant procedures.

4.3.2 Prototype Implementation

The 5MBS prototype began development in two European R&D projects: 5G-TOURS [131] and FUDGE-5G[114]; and the development is currently ongoing. As previously mentioned, the prototype relies on modifications to the Open5GCore source code, including changes to Open5GCore internal libraries and additional code added to the functions themselves. Inside the prototype, the UPF and SMF were extended to become the MB-UPF and MB-SMF respectively; and the NEF was updated to support new service procedures. The rest of the Core NFs required were not modified. In summary, the MB-UPF and MB-SMF enable the 5MBS Shared Delivery, which is shown in figure 4.9. The following list includes the detailed 5MBS functionality included per NF:

- MB-UPF has been modified to support IPv4 multicast group addresses. The MB-UPF is extended to apply its PDR to multicast transmissions, based on a pair of two different multicast IP addresses: One for the incoming source content, usually a video server; and the internal multicast address for the N3mb interface, between a group of gNBs and the MB-UPF. To identify different Multicast MBS Sessions, an assigned Common TEID or C-TEID is used alongside the pair of multicast addresses. While 3GPP recommends to use a random TEID per GTP tunnel for security reasons, inside the prototype hard-coded reserved values are used, to avoid TEID collisions between unicast and multicast transmissions. The GTP-U protocol used in the N3mb interface is not modified, as it already supports multicast [132]. The MB-UPF manages the IGMP multicast groups between the gNBs over the N3mb interface, which have been divided into a N3mb multicast IP per multicast service, and another multicast IP towards the AF which identifies the service itself. The user commands provided by the Open5GCore to operate the UPF have been extended with new specific 5MBS commands.

- MB-SMF supports the management of TMGIs, used in the creation and deallocation of Multicast MBS Sessions. The services implemented are the *Nmbsmf_TMGI* and *Nmbsmf_MBSSession* and exposed via NEF towards external AFs. *Nmbsmf_TMGI* includes the management of TMGIs that identify the Multicast MBS Sessions, with the operations "Allocate" and "Deallocate". *Nmbsmf_MBSSession* include the management of Multicast MBS Sessions, with the operations "Create" and "Delete". Optionally, an API has been implemented so that the MB-SMF can act as a trusted AF towards the 5GC and create or destroy Multicast MBS Sessions based on user input; triggering the delivery of the corresponding MBS Session information over N4 to the MB-UPF so it prepares the multicast tunnel in the User Plane. The user commands provided by the Open5GCore to operate the SMF have been extended with new specific 5MBS commands.

- NEF API has been modified to support non-trusted AF northbound point to trigger the launch of Multicast MBS Sessions. Two MBS specific API calls have been implemented in the prototype.

  Nnef_MBSTTMGI exposes the management of the TMGIs, providing the operations "Allocate" and "Deallocate".*Nnef_MBSSession* enables exposure of "Create" and "Delete" operations, in order to manage MBS Sessions. The user commands provided by the Open5GCore to operate the NEF have been extended with new specific 5MBS commands.

However, in order to validate the development performed, it was necessary to have a functional end-to-end transmission chain that can provision several users and gNBs to verify that multicast development was working properly. At the current moment of writing, no commercial gNB or 5G device implements the 5MBS features. To solve this situation, a new software function was included to bridge the connection between the N3mb multicast interface and the gNBs, known as the IGMP endpoint and incorporated inside of the emulated gNB functionality. This component transforms the multicast IP used by the GTP tunnel into an unicast one for legacy and non-multicast capable device attached to the network, effectively providing backwards compatibility with legacy gNBs. Figure 4.10 shows a diagram of the prototype.

The current version of the prototype provides a basic functionality of 5MBS, allowing the Shared Delivery Mode between several gNBs and the MB-UPF. The set of features implemented have been validated with the Open5GCore Benchmarking Tool, which provides an emulated Radio and Device Layer. In this setup, each emulated gNBs has an associated internal IGMP endpoint in the User Plane. The set of IGMP endpoints join the multicast group offered by the MB-UPF before the transmission begins. The emulated gNBs do not implement the full NG-RAN stack, and will forward the application packets coming the MB-UPF to the UEs without the headers. Emulated UEs are represented as Linux terminals, which allow for Linux-based software tools to

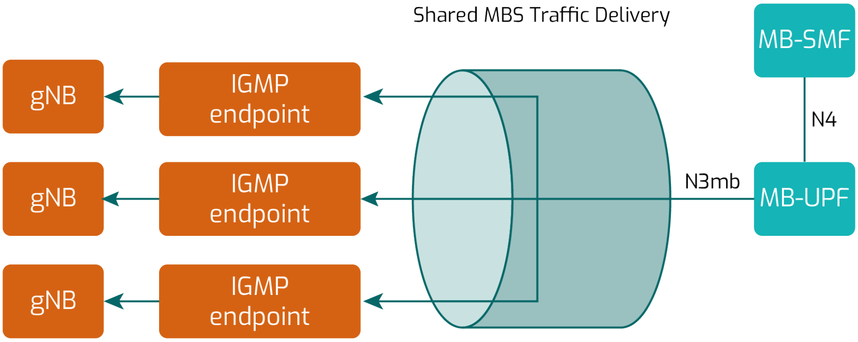


Figure 4.10: Diagram of the 5MBS Prototype, including the new IGMP endpoint that enables the backwards support with Release 15 gNBs. Extracted from [130]

executed. Leveraging this, the initial development validation has been perform with *socat* and *iperf*. A more elaborate test using *ffmpeg* on each emulated UE receive and play multimedia video; which is served by a network host using the software *ffmpeg* over a multicast IP address that delivers UDP packets. More details about this test can be found in [130].

Figure 4.11: Example screenshot of an example two virtualized UEs, displaying video using *ffplay* over 5MBS in an Ubuntu environment

4.4 Performance of the 5MBS prototype

The previous section detailed the 5MBS prototype, the components that form it and the implemented features. As it was noted, the validation test performed were focused on feature evaluation. Instead, this section analyses the performance differences in terms of: packet loss when using MBS NFs when compared to unicast NFs; and the network resources from using multicast transmissions against a variable number of users. To do so, the performance test have been structured in a single battery of tests for multicast delivery using the 5MBS prototype. The rest of the section is structured as follows: The system model for the multicast test is described. Then, the methodology setup on how the test have been performed is explained. After that, the results are presented and discussed in the last subsection.

4.4.1 System model and considered scenarios

The system model used to evaluate the 5MBS prototype is composed of two different parts. One is a setup to perform a bandwidth calibration of the Open5GCore using *iperf* while the other is a scalability test using *ffmpeg* to deliver video over different topologies of users and gNBs. For both tests, several preliminary steps need to be setup before doing the experiments, in detail: The modified Open5GCore is launched normally, then the prototype is executed by using a template with the number of virtualized gNBs, devices, and multicast services which are needed to create the forwarding rules. Additional parameters in this template include a TMGI and C-TEID to the MB-SMF and the gNBs; and the multicast pair of addresses, one for the N3mb tunnel and the other for the video delivery transmission between the MB-UPF and the Network Host. Once these parameters in the template are set and configured, the following steps are performed: first, the modified Open5GCore with the MB-UPF and MB-SMF is executed; then, a variable number of virtualized gNBs are connect to the MB-UPF, then, one or more UEs are attached to each gNB. The MB-UPF has been provisioned with route forwarding, encapsulates the multicast packets with GTP-U, and puts the packets in the N3mb interface towards the IGMP end-points inside the virtualized gNBs. The next step involves the UEs joining the **source multicast group** of the multicast traffic. Finally, the MB-SMF creates the MBS Session, using the preconfigured TMGI and pair of multicast addresses. The MB-SMF automatically creates any required PFCP rules internally. A script that automated this process has been made by the laboratory personnel.

For multicast, the system model features Open5GCore providing the MB-SMF, MB-UPF, and the required NFs to provide connectivity (AMF, AUSF,

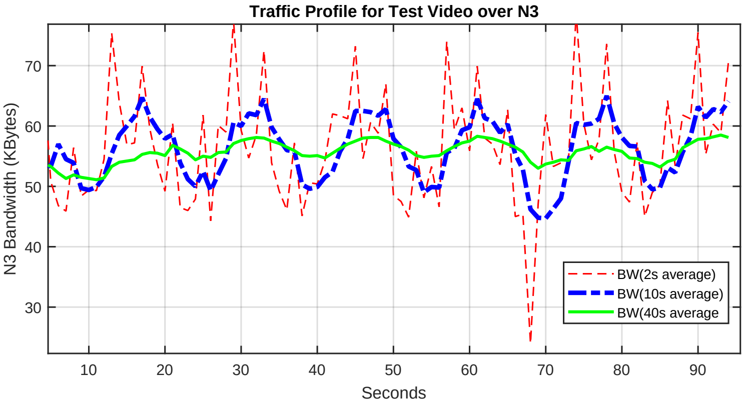
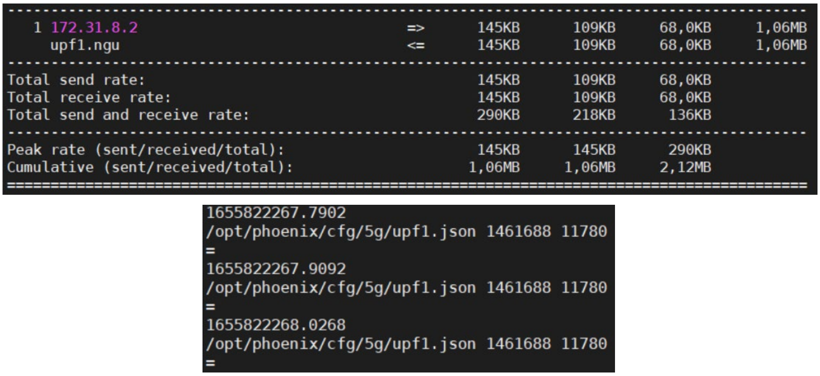


Figure 4.12: Temporal values of the bandwidth coursed through the N3 interface, which connects the UPF and a gNB. Each line correspond with different moving average over 2, 10 and 40 seconds, extracted from the output of *iftop* Linux terminal command. The video used is a 720p resolution and 30 frames per second. The video delivery has been done using *ffmpeg*, between a Network Host and an emulated UE and NG-RAN provided by the Open5GCore Benchmarking Tool

UDM, NEF and NRF). Again, the radio is emulated by using the Open5GCore Benchmarking Tool, which deploys a virtual gNB and a UE which execute the required signaling to attach and transmit traffic to the network. A Network Host is also deployed, which will connect via N6 to the MB-UPF, and send a video using a *ffmpeg* script. A fragment of the bandwidth captured over N3mb interface in the 5G Core is shown in Figure 4.12, when delivering video using ffmpeg. At the device layer, the UEs receive the content using a different *ffmpeg* script, and if GUI is enabled, can display the video (for no GUI terminals, the option *-nodisp* is added). The test is run for the duration of the test video, in this case, two loops of 2 minutes and 47 seconds, then the test is over and the results analysed. The metric to measure in this preliminary performance study is the bandwidth coursed through the N3mb. The N3mb connects the MB-UPF, which manages the multicast tunnels, with a group of gNBs. By monitoring and comparing the amount of the traffic coursed as the number of UEs increases, a comparison can be made of how efficient multicast is in terms of network resources, since the delivery of multicast of 1 UE is considered the initial benchmark. The tool used to monitor the bandwidth is a Linux script based on the command *iftop* [133]; which outputs every two seconds the bandwidth and displays it averaged by 2, 10 and 40 seconds long buffers. A



```
--------------------------------------------------------------------------------------------
   1 172.31.8.2                               =>      145KB      109KB     68,0KB     1,06MB
     upf1.ngu                                 <=      145KB      109KB     68,0KB     1,06MB
--------------------------------------------------------------------------------------------
Total send rate:                                      145KB      109KB     68,0KB
Total receive rate:                                   145KB      109KB     68,0KB
Total send and receive rate:                          290KB      218KB      136KB
--------------------------------------------------------------------------------------------
Peak rate (sent/received/total):                      145KB      145KB      290KB
Cumulative (sent/received/total):                    1,06MB     1,06MB     2,12MB
============================================================================================
```

```
1655822267.7902
/opt/phoenix/cfg/5g/upf1.json 1461688 11780
=
1655822267.9092
/opt/phoenix/cfg/5g/upf1.json 1461688 11780
=
1655822268.0268
/opt/phoenix/cfg/5g/upf1.json 1461688 11780
=
```

Figure 4.13: Screenshot of an example unicast capture, using Linux-based tools to measure the Bandwidth on the upper side, and the VSZ and RSS values of the RAM on the bottom side.

capture of the output of the bandwidth measurement script can be seen on the upper side of Figure 4.13.

4.4.2 Performance results and discussion

The results have been gathered from multicast deployments. The environment is an Ubuntu virtual machine in a Proxmox 4 server, with 4 cores [134] of 2.1 GHz processing speed and 4 GB of RAM allocated. The multicast prototype shares most of the computational environment as the unicast connections, as the functions are extensions of the unicast counterparts. As previously mentioned, the first test is a bandwidth calibration, to observe how does the baseline 5G NFs and the 5MBS ones respond to a bandwidth stress test using the Linux tool *iperf*. To do so, a Network Host running an iperf server connects to the MB-UPF over the N6mb, which will deliver the test traffic to the emulated RAN and devices, which run the iperf client. The traffic chosen for the initial calibration benchmarking is UDP, both with multicast and unicast, sent in 1 second intervals over 300 seconds, while varying the bandwidth delivered. The test was used to choose the parametrization of the Open5GCore and to obtain the maximum bandwidth that can be coursed over the new multicast interfaces and the comparison against the unicast ones. The range of bandwidth chosen is 1, 2, 5, 10, 15, 20, 35 and 50 Mbits/s, repeated for unicast and multicast connectivity. The metrics gathered are the percentage of lost packets and the presence or absence of datagram disordering in the client. The results are reflected in Table 4.2: It can be seen how the performance of unicast and multicast is not affected until the 35 Mbit/s bandwidth test; where the packets

Table 4.2: iperf bandwidth calibration tests

Type of Traffic	Bandwidth	Datagram Disordering	% of lost datagrams
Unicast	1 Mbit/s	No	0%
Unicast	2 Mbit/s	No	0%
Unicast	5 Mbit/s	Yes	0%
Unicast	10 Mbit/s	Yes	0%
Unicast	15 Mbit/s	Yes	0%
Unicast	20 Mbit/s	Yes	0%
Unicast	35 Mbit/s	Yes	0.88%
Unicast	50 Mbit/s	Yes	14%
Multicast	1 Mbit/s	No	0%
Multicast	2 Mbit/s	No	0%
Multicast	5 Mbit/s	No	0%
Multicast	10 Mbit/s	Yes	0%
Multicast	15 Mbit/s	Yes	0%
Multicast	20 Mbit/s	No	0%
Multicast	35 Mbit/s	No	0.75%
Multicast	50 Mbit/s	Yes	22%

start to being drop at UE side. The reasons for this bandwidth limit surge from the several abstraction layers of the 5MBS prototype, as it is on-boarded on a Virtual Machine, and each NF of the Open5GCore is connected with each other using network namespaces and networked using virtual bridges. On the results themselves, unicast performs better at 50 Mbit/s, experiencing 14% of packet loss while the multicast counterpart features 22% for the iperf test duration; highlighting a degradation of 63% increased packet loss.

The value of 35 Mbit/s has been taken into account in order to specify the video bandwidth and codec. In detail, the video used in the experiments is a mobile video recorded at 4K quality, with 2:47 minutes duration, H.264 as compression codec and 6 Mb/s average bitrate. The video is run twice, and started manually, to see the effect of the bandwidth drop over the N3mb interface. A variable number of virtual UEs have been tested: 1, 2 and 3. The multicast results can be seen in Figure 4.14. From the results, three main points can be derived: First, the decrease in bandwidth in the middle of graphs corresponds to where the video is relaunched manually. Depending on the timing and the processor queue, the stop in the video delivery varies as well. Second, it can be seen that the transmission peaks around 12 Mbit/s. This value may be the maximum bitrate that be coursed with the current 5GC parametrization, including the VM capabilities and the abstraction layers added. Further studying of different video qualities, VM characteristics or other deployment topologies influence the maximum bitrate value. Last, while the 2 seconds average line from graph to graph slightly varies from case to case, the longer averages highlight how the bandwidth coursed is independent of the UEs which have joined the 5MBS transmission. This provides validation that the MB-UPF is not replicating packets per UE and it is using a single tunnel from the Core to the RAN to deliver the video. It can be concluded that multicast saves bandwidth resources in the data plane when users consume live content. The graphs shown in Figure 4.15 showcase a different scenario: 2 UEs consuming 2 distinct services, but the number of gNBs is variable between 1 and 2. In this case, the goal was to evaluate if the number of gNBs does affect the bandwidth. The video chosen was a lower bitrate compared to previous validation test in order to avoid the transmission peaks, with an average bitrate of 1.6 Mb/s and in a similar way, it is launched twice to double the duration. It can be noticed in the graphs that, while the peak values coincide, the shape is fundamentally different. The reason for this is the human factor, where the tests are not automated and each video service, UE, monitoring tool launch, stop and restart needs to be performed manually, introducing randomness into the measurement experiment. Nevertheless, the graphs show both bandwidth reductions around the middle duration, marking the restart time of the videos inside the prototype. The main conclusion derived from this experiment is that the number of gNBs attached to the MB-UPF does not affect the bandwidth coursed over the N3mb interface.

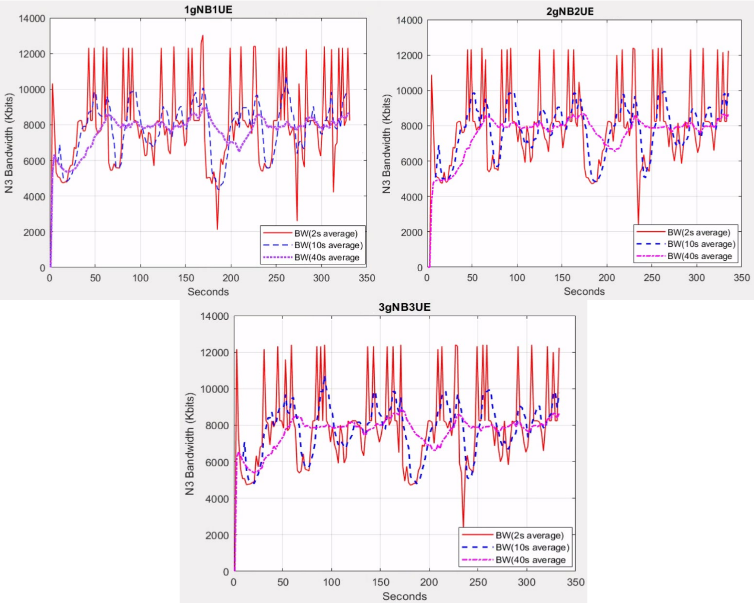


Figure 4.14: Bandwidth coursed through the N3mb interface of the 5MBS prototype, extracted with the linux command *iftop*. The UEs and gNBs are 1 and 1, 2 and 2, 3 and 3. A single multicast flow is delivered from a network host, which enters the MB-UPF via the N6 interface.

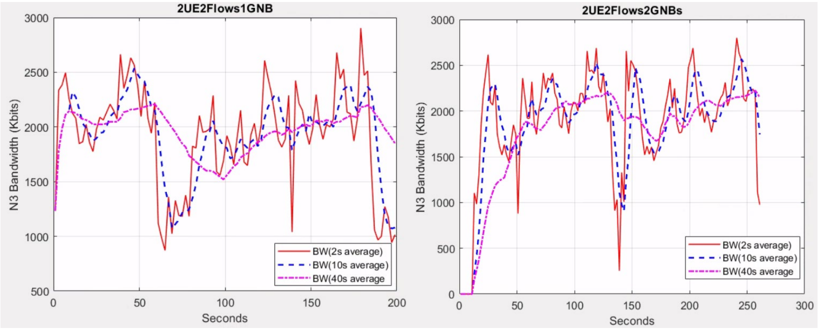


Figure 4.15: Bandwidth coursed through the N3mb interface of the 5MBS prototype, extracted with the linux command *iftop*. The UEs are fixed to 2, each consuming its own service, while the gNBs vary from 1 in the left graph and 2 in the right one.

Chapter 5

Conclusions and Future Work

This dissertation has investigated and evaluated the possibilities to provision point-to-multipoint services in 5G Networks. The work here is nowhere finished as the situation quickly changes. It is possible that in the coming years, the latest iteration of eMBMS becomes the first global broadcast standard, as the deployment momentum gains pace. Particularly for Europe, it is waiting on the resolution of the WRC-23, where the fate of the 600-700 MHz will be decided. Broadcasters which adopt a 5G mobile technology also able to provide broadcast may get an advantage in spectrum concessions and auctions versus their peers. The immediate conclusion derived from this thesis is how the existing regulatory spectrum framework is restraining the raise of novel business models, for example, use of broadcast infrastructure alongside cellular one. The use of the Citizens Broadband Radio Service (CBRS) band in USA should be an example, where local business and tenants can apply for small segments of the spectrum in a cost-effective way. This section is structured as follows: Section 5.1 summarizes the findings of the thesis, chapter by chapter; while Section 5.2 presents topics for future study directly related to the thesis.

5.1 Concluding Remarks

5.1.1 Pre-Release 17 Mobile Broadcasting

The point-to-multipoint solution in LTE Networks is known as eMBMS, introduced in Release 8. This technology was made to provide Mobile Broadcast, but the initial versions of the standard were not suitable to serve as a full Terrestrial Broadcast standard capable of reaching pedestrian devices and roof-top antennas alike. It was until Release 14 that the new iteration of the feature, ENTV, started to be a viable solution for broadcasters to deploy. Yet, eMBMS features a lot of limitations, in part of the backwards-compatible philosophy of 3GPP. The research efforts to provide preliminary broadcast studies in 5G evaluated this. In particular, the 5G-Xcast project, detailed in the thesis, provided a top-down solution for the delivery of point-to-multipoint services in 5G networks; by taking a blank-slate approach. The project did also consider other verticals beyond Terrestrial Broadcast in the design, like PWS or IoT. The end result was a modified Air Interface, cloud based RAN, and two 5GC architectures to address all the requirements from the verticals. The thesis also provides two examples of the use of eMBMS outside of the Media and Entertainment: one for the provision of time synchronization of IoT devices, and the other for the complementary use alongside Cell Broadcast to enrich the alerts in PWS.

5.1.2 Convergence of Terrestrial and Mobile Networks

Another possibility to tackle the provision of point-to-multipoint services is to converge existing Terrestrial Networks and their standards with 5G Mobile Networks; so Terrestrial Broadcast can become the point-to-multipoint solution of 5G. To do so, an study of the existing convergent solutions and ecosystem was carried out, identifying the ways inside and outside of 3GPP that this joint collaboration could be carried out. In Release 16, 3GPP introduced the framework named ATSSS, to allow for the dual use of non-3GPP Access Networks, like Wi-Fi, and 3GPP ones. The thesis evaluated if the current ATSSS was enough to enable the Layer-3 or IP layer convergence of ATSC 3.0 Terrestrial Broadcast Networks with 5G ones. A list of limitations was derived based on the qualitative analysis; accompanied with a novel architecture, based on QUIC, which could support and provide Convergent Services.

5.1.3 5MBS Mobile Broadcasting and prototype evaluation

Release 17 was the first 5G standard to include point-to-multipoint services in a native 5G environment called 5MBS. The standardized system is capable of providing broadcast and multicast while using unicast as a backup mode to ensure service continuity in non-5MBS network. To evaluate the performance, a software prototype which features partial implementation of 5MBS was used as a benchmarking tool. The prototype features the MB-SMF, MB-UPF and the

N3mb interface and it is implemented as an extension of the commercial 5GC known as Open5GCore. The radio layer is provided via emulation, where the gNB and UE are virtual endpoints which will receive the multicast data. The performance evaluation studied the impact in terms of bandwidth in the N3mb interface, served by an experimental MB-UPF that handles video streams delivered from a local network host. In detail, the use of 5MBS in the prototype to deliver multimedia video offers a scalable solution independent of the number of UEs to deliver live content.

5.2 Future work

5.2.1 5MBS in Release 18

The first version of 5MBS has been finished in 2022, as detailed in Chapter 4. However, the specification is far from complete, and future 5G-Advanced releases will keep iterating on the system, solving limitations and adding new features. In Release 18, the following topics of 5MBS are going to be addressed: Support of RRC_Inactive state, RAN sharing, allowing trusted AF to trigger MBS Sessions, and performance in PWS scenarios. Another interesting topic to research is the addition of Satellite Networks alongside 5MBS. NR has a profile for satellite links, also named Non-Terrestrial Networks (NTN); alongside the consideration of satellite background infrastructure for cellular networks. It is also noteworthy to monitor 5MBS in research environments and public organizations, like 5G-MAG, where projects and initiatives can identify limitations and provide novel solutions, outside of standardization entities.

5.2.2 5MBS Prototype development

The prototype implements a partial suite of 5MBS features. The functionalities and stability of the Prototype will be improved during the coming months. There are plans of interoperability test as part of the 5G-MAG Reference Tools group [135]. As the prototype has been created in a research environment, more extensive performance trials that the ones carried in this thesis could be done. The emulated RAN and UE layers can be updated into actual physical ones, using public initiatives or collaborating with private companies. Other topic for consideration is the evaluation of Network Slicing technologies in the prototype, to ensure deterministic QoS and service isolation across unicast and multicast slices. A paper highlighting 5MBS, the prototype and the study is planned.

5.2.3 Cloud deployment analysis for TV Broadcasting

5G was designed with cloud principles in mind. No Terrestrial Broadcast standard has done the same exercise. It remains as a line of research to evaluate the possible cloudification of Terrestrial Broadcast infrastructure. But it presents similar problems to the 5G UPF. Some functions require strict timings and cannot be virtualized or deployed in the cloud, as the addition of several abstraction layers introduces extra latency and uncertain jitter. This is especially problematic for SFN communications, where a badly synchronized transmitter will interfere with the rest of the network. The study and challenges of cloud-based technologies applied to broadcast distribution is pending. The incorporation of Multiaccess Edge Computing (MEC) technologies for distributed deployments in Broadcasting needs to be considered as well, to reduce the overall latency and synchronization requirements of SFN networks.

5.2.4 6G Broadcast

5MBS reused NR without any modifications as the Physical Layer. Yet, due to Cyclic Prefix and other waveform parametrization; this signal is not suitable for Terrestrial Broadcast infrastructure. Trying to adapt NR with new waveforms could experience the same problems than eMBMS did: lack of manufacturer adoption since the business model was not clearly identified. A new mobile standard, such as 6G, that incorporates Point-to-Multipoint capabilities from the very initial stages can be highly beneficial. It was mentioned in Chapter 1 how the use of Point-to-Multipoint to offload video is a scalable way to handle the ever-rising demand for mobile data. 6G could also incorporate many of the research work done in the Physical Layer, such as superposition of signals [136] or wideband transmissions [137].

Acronyms

AF Aplication Function

ALP ATSC Link-Layer Protocol

AL-FEC Application Layer Forward Error Correction

AMF Access and Mobility Function

API Application Programming Interface

ASO Analog Switch-Off

ATSC Advanced Television Systems Committee

ATSSS Advanced Traffic Steering, Switching and Splitting

AUSF Authentication Server Function

BM-SC Broadcast Multicast Service Centre

BNO Broadcast Network Operator

CAS Cell Adquisition Subframe

CBRS Citizens Broadband Radio Service

CCAM Cooperative, Connected and Automated Mobility

CDN Content Delivery Network

CNF Containerized Network Function

LIST OF ABBREVIATIONS

CotS	Commercial off the Shelf
CPGWF	Control Plane Gateway Function
CPM	Conference Preparatory Meeting
CUPS	Control and User Plane Separation
DCI	Downlink Control Information
DNS	Domain Name System
DTMB	Digital Terrestrial Multimedia Broadcast
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
eMBB	enhanced Mobile BroadBand
eMBMS	enhanced Multicast Broadcast Multimedia Services
ENTV	Enhanced Television Services over 3GPP eMBMS
EPC	Evolved Packet Core
EPG	Electronic Programme Guide
ETRI	Electronics and Telecommunications Research Institute
EU	European Union
FEC	Forward Error Correction
FEF	Future Extension Frame
FLUTE	File-based Delivery over LTE-based eMBMS
gNB	next generation Node B
gNB-CU	gNB Control Unit

gNB-DU gNB Distributed Unit

GPU Graphic Processing Unit

GUI Graphical User Interface

HARQ Hybrid Automatic Repeat Request

HbbTV Hybrid Broadcast Broadband Television Standard

HDTV High Definition TV

HDR High Dynamic Range

HFR High Frequency Range

HPHT High-Power High-Tower

ICT Information and Communication Technology

IMSI International Mobile Subscriber Identity

IMT International Mobile Telecommunications

IoT Internet of Things

ISD Intersite Distance

ISDB-T Integrated Services Digital Broadcasting Terrestrial

ITU International Telecommunications Union

LLS Lower Layer Signalling

LPLT Lower-Power Low-Tower

LTE Long Term Evolution

MA PDU Multiaccess Packet Data Unit

MAC Medium Access Control

MEC Multiaccess Edge Computing

MBMS-GW Multicast Broadcast Multimedia Services Gateway

MBSF Multicast Broadcast Service Function

MBSFN Multicast Broadcast Single Frequency Network

MBSTF Multicast Broadcast Service Transport Function

MB-SMF Multicast Broadcast Session Management Function

MB-UPF Multicast Broadcast User Plane Function

MBMS Multicast Broadcast Multimedia Services

MCCH Multicat Control Channel

MCE Multicast Coordinator Entity

MCG Mobile Communications Group

MCH Multicast Channel

MIMO Multiple Input Multiple Output

MLD Multicast Listener Discovery

mmW millimetric Wave

mMTC massive Machine Type Communications

MMTP MPEG Media Transport Protocol

mmWave millimetric Wave

MNO Mobile Network Operator

MooD Multicast operation on Demand

MPTCP Multipath Transport Control Protocol

MTCH Multicast Transport Channel

NEF Network Exposure Function

NF Network Function

NFV Network Function Virtualization

NPN Non-Public Network

NR New Radio

NRF Network Repository Function

NSA Non-StandAlone

NSSF Network Slice Selection Function

NTN Non-Terrestrial Networks

NTP Network Time Protocol

N3IWF N3 Interworking Function

OFDM Orthogonal Frequency-Division Multiplexing

PCF Policy Control Function

PDCCH Packet Downlink Control Channel

PDCP Packet Data Convergence Protocol

PDR Packet Detection Rule

PDSCH Physical Downlink Shared Channel

PDU Protocol Data Unit

PHY Physical Layer

PIM Protocol Independent Multicast

PLP Physical Layer Pipe

PMCH Physical Multicast Channel

PPDR Public Protection and Disaster Relief

PSM Public Service Media

PtM Point-to-Multipoint

PtP Point-to-Point

PW Public Warning

PWS Public Warning System

QCI QoS Class Identifier

QoS Quality of Service

QUIC Quick UDP Internet Connections

RAN Radio Access Network

RAT Radio Access Technology

RLC Radio Logical Channel

RNTI Radio Network Temporary Identifier

ROM Receive Only Mode

ROUTE Real-time Object delivery over Unidirectional Transport

RRC Radio Resource Control

RRH Remote Radio Head

RSPG Radio Spectrum Policy Group

RTT Return Trip Time

SA Stand-Alone

SAI Service Area Identifier

SBA Service Based Architecture

SBI Service Based Interface

SC-MCCH Single Cell Multicast Control Channel

SC-PTM Single Cell Point-to-Multipoint

SDAP Service Data Adaptation Protocol

SDN Software-Defined Networking

SFN Single Frequency Networks

SI Study Item

SIB Signal Information Block

SLS Service Layer Signalling

SMF Session Management Function

SUPI Subscription Permanent Identifier

SVC Scalable Video Coding

TMGI Temporary Mobile Group Identity

TNGF Trusted Non-3GPP Gateway Function

TTA Time To Air

TWIF Trusted WLAN Interworking Function

UDM Unified Data Management

UDR Unified Data Repository

LIST OF ABBREVIATIONS

UHD Ultra High-Definition

UHF Ultra-High Frequency

UMTS Universal Mobile Telecommunications System

UPF User Plane Function

UPGWF User Plane Gateway Function

URLLC Ultra Reliable Low-Latency Communications

USD User Service Description

USRP Universal Software Radio Peripheral

VLAN Virtual Local Area Network

VM Virtual Machine

VOD Video on Demand

V2X Vehicular To Everything

WLAN Wireless Local Area Network

WG Working Group

WI Work Item

XCF Xcast Control Function

XUF Xcast User Function

3GPP Third Generation Partnership Project

4G Fourth Generation Mobile Network

5G Fifth Generation Mobile Network

5GC 5G Core

5GMS 5G Media Streaming

5GS 5G System

5MBS 5G Multicast Broadcast Services

References

[1] Mobile data traffic outlook. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/mobile-traffic-forecast

[2] T. Wang, *Spectrum Analysis and Regulations for 5G*, 2017, pp. 27–50.

[3] R. Conseil, “The Economic Benefit of Broadcast Offload in Mobile Data Delivery,” White Paper, TDF, Apr. 2015.

[4] D. Schien, “Using Behavioural Data to Assess the Environmental Impact of Electricity Consumption of Alternate Television Service Distribution Platforms,” White Paper, BBC Research, Sep. 2020.

[5] Superior media experiences by broadcasting content. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/mobility-report/articles/superior-media-experiences-by-broadcasting-content

[6] Evolution to lte report, 2017. [Online]. Available: https://gsacom.com/paper/lte-broadcast-embms-global-status-summary-deployments-activities/

[7] D. Turina and T. Lohmar, “Mobile tv - the concept overview and technology enablers,” in *2007 9th International Conference on Telecommunications*, 2007, pp. 345–345.

[8] Qualcomm shutters flo tv â€˜ mediaflo not far behind. [Online]. Available: https://rethinkresearch.biz/articles/qualcomm-shutters-flo-tv-mediaflo-not-far-behind/

[9] D. T. Research. (2022, Feb.) Number of TV households worldwide from 2010 to 2026 . Statista, https://www.statista.com/statistics/268695/number-of-tv-households-worldwide/. Digital TV Research.

[10] K. Donders, *Public Service Media and the European Internal Market: Friends or Allies?* Digiworld N.101, 2016, pp. 42–61.

[11] I. S. Reljin and A. N. Sugaris, “Dvb standards development,” in *2009 9th International Conference on Telecommunication in Modern Satellite, Cable, and Broadcasting Services*, 2009, pp. 263–272.

[12] ATSC, “A/322. physical layer protocol,” Advanced Television Systems Committee, Standard, 3 2022. [Online]. Available: https://muygs2x2vhb2pjk6g160f1s8-wpengine.netdna-ssl.com/wp-content/uploads/2022/04/A322-2022-03-Physical-Layer-Protocol.pdf

[13] What is cloud native? [Online]. Available: https://www.oracle.com/cloud/cloud-native/what-is-cloud-native/

[14] “Radio Regulations, edition of 1947,” ITU, http://handle.itu.int/11.1004/020.1000/1.7, 1947.

[15] “ Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06) ,” ITU-R, http://handle.itu.int/11.1002/pub/801af205-en, 2006.

[16] “ Final Acts WRC-12, World Radiocommunication Conference ,” ITU-R, http://handle.itu.int/11.1002/pub/805627a4-en, 2012.

[17] “ Final Acts WRC-19, World Radiocommunication Conference ,” ITU-R, http://handle.itu.int/11.1002/pub/813b5921-en, 2019.

[18] D. Ratkaj. (2021, Nov.) SPECTRUM USE AND NEEDS IN THE UHF BAND ACROSS REGION 1. Forecast 2021. European Broadcaster Union.

[19] “ Results of the first session of the Conference Preparatory Meeting for WRC-23 ,” ITU-R, https://www.itu.int/md/{{3GPP}}-CA-CIR-0251/en, 2019.

[20] A. Jha and D. Saha, “Why is 700 mhz band a good proposition for provisioning pan-india 4g lte services?: A comparative techno-economic evaluation study,” in *2017 9th International Conference on Communication Systems and Networks (COMSNETS)*, 2017, pp. 229–236.

[21] B. Commission. (2020, Sep.) The State of Broadband: Tackling digital inequalities. A decade for action. ITU Website. ITU.

[22] M. Matinmikko, M. Mustonen, and H. Haapasalo, "Stakeholder analysis for future use of the ultra-high frequency (uhf) band," *International Journal of Technology, Policy and Management*, vol. 17, p. 159, 01 2017.

[23] S. Rommer, P. Hedman, M. Olsson, L. Frid, S. Sultana, and C. Mulligan, "Chapter 1 - introduction," in *5G Core Networks*, S. Rommer, P. Hedman, M. Olsson, L. Frid, S. Sultana, and C. Mulligan, Eds. Academic Press, 2020, pp. 1–5.

[24] Itu towards "imt for 2020 and beyond". [Online]. Available: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx

[25] 3GPP, " Study on UPF enhancement for Exposure And SBA," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 23.700, 09 2022, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=4013

[26] F. Rinaldi, A. Raschellà, and S. Pizzi, "5g nr system design: a concise survey of key features and capabilities," *Wireless Networks*, vol. 27, 11 2021.

[27] Ric, xapps, rapps: Who are the key players? [Online]. Available: https://stlpartners.com/articles/telco-cloud/ric-xapps-rapps-who-are-the-key-players/

[28] A. Shokrollahi, "Raptor codes," *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2551–2567, 2006.

[29] R. Belda, I. de Fez, F. Fraile, P. Arce, and J. C. Guerri, "Hybrid flute/dash video delivery over mobile wireless networks," *Transactions on Emerging Telecommunications Technologies*, vol. 25, no. 11, pp. 1070–1082, 2014.

[30] Enensys, "Technical Overview of Single Frequency Network," White Paper, Enensys Technologies, Nov. 2008.

[31] 3GPP, " MBMS synchronisation protocol (SYNC)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 25.446, 04 2022, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=1210

[32] H. Wang, H. Vandervelde, and S. Kim, “Lte mbms sync protocol for support synchronisation of content,” in *2009 IEEE International Conference on Communications Technology and Applications*, 2009, pp. 392–395.

[33] 3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.300, 04 2022, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2430

[34] ——, “ Multimedia Broadcast/Multicast Service (MBMS) user services; Stage 1,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 22.246, 01 2022, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=635

[35] A. Daher, M. Coupechoux, P. Godlewski, P. Ngouat, and P. Minot, “Sc-ptm or mbsfn for mission critical communications?” in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, 2017, pp. 1–6.

[36] D. Gomez-Barquero, J. J. Gimenez, and R. Beutler, *3GPP Enhancements for Television Services: LTE-Based 5G Terrestrial Broadcast*. John Wiley & Sons, Ltd, 2020, pp. 1–10. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/047134608X.W8410

[37] J. J. Gimenez, J. L. Carcel, M. Fuentes, E. Garro, S. Elliott, D. Vargas, C. Menzel, and D. Gomez-Barquero, “5g new radio for terrestrial broadcast: A forward-looking approach for nr-mbms,” *IEEE Transactions on Broadcasting*, vol. 65, no. 2, pp. 356–368, 2019.

[38] 3GPP, “Study on scenarios and requirements for next generation access technologies,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 38.913, 04 2022, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2996

[39] ——, “ Evolved Universal Terrestrial Radio Access (E-UTRA); Study on LTE-based 5G terrestrial broadcast,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 36.776, 03 2019, version 16.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3500

[40] Rohde & schwarz and qualcomm show 5g broadcast system at imc22. [Online]. Available: https://www.broadbandtvnews.com/2022/09/30/rohde-schwarz-and-qualcomm-show-5g-broadcast-system-at-imc22/

[41] First multi-site 5g broadcast trials deliver eurovision song contest in italy, austria, france and germany. [Online]. Available: https://www.broadbandtvnews.com/2022/05/10/first-multi-site-5g-broadcast-trials-deliver-eurovision-song-contest/

[42] Tv over broadcast in terrestrial broadcast networks (ateme, france tv, qualcomm).

[43] J. Costa-Requena, C. B. Estevan, and S. Borenius, "Transport layer and synchronization for smart grid and industrial internet in 5g networks," in *2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, 2019, pp. 1–5.

[44] 3GPP, "MBMS for Internet of Things (IoT)," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 26.850, 09 2018, version 16.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3246

[45] GSMA. (2013, Jan.) Mobile Network Public Warning Systems and the Rise of Cell-Broadcast. GSMA Website, https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2013/01/Mobile-Network-Public-Warning-Systems-and-the-Rise-of-Cell-Broadcast.pdf . GSMA Disaster Response.

[46] One2Many. (2020, Dec.) NEW ZEALAND'S NATION WIDE EMERGENCY MOBILE ALERT PROJECT, USING CELL BROADCASTING TECHNOLOGY. One2Many Website. One2Many.

[47] T. Jokela, J. Kalliovaara, M. Bot, H. Kokkinen, B. Altman, C. Barjau, P. Sanders, D. Gomez-Barquero, and J. Paavola, "Multimedia public warning alert trials using embms broadcast, dynamic spectrum allocation and connection bonding," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 571–578, 2020.

[48] T. Tran, "Mobile core network," 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 6 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_D4.1_v2.0_web.pdf

[49] D. Gomez-Barquero, "5G-Xcast Overview," p. 1. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2018/07/5G-Xcast_Tutorial_03_5G-Xcast_Overview.pdf

[50] M. Fuentes, J. L. Carcel, C. Dietrich, L. Yu, E. Garro, V. Pauli, F. I. Lazarakis, O. Grøndalen, O. Bulakci, J. Yu, W. Mohr, and D. Gomez-Barquero, "5g new radio evaluation against imt-2020 key performance indicators," *IEEE Access*, vol. 8, pp. 110 880–110 896, 2020.

[51] 3GPP, "Service requirements for the 5G system," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 22.261, 09 2022, version 19.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3107

[52] D. Mi, J. Eyles, T. Jokela, S. Petersen, R. Odarchenko, E. Öztürk, D.-K. Chau, T. Tran, R. Turnbull, H. Kokkinen, B. Altman, M. Bot, D. Ratkaj, O. Renner, D. Gomez-Barquero, and J. J. Gimenez, "Demonstrating immersive media delivery on 5g broadcast and multicast testing networks," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 555–570, 2020.

[53] T. Tran, D. Navratil, P. Sanders, J. Hart, R. Odarchenko, C. Barjau, B. Altman, C. Burdinat, and D. Gomez-Barquero, "Enabling multicast and broadcast in the 5g core for converged fixed and mobile networks," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 428–439, 2020.

[54] J. Hart, "Converged core network," 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 6 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_D4.2_v3.0_web.pdf

[55] B. Altman, "Session control and management," 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 5 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_D4.3_v2.0_web.pdf

[56] D. Vargas, "Lte-advanced pro broadcast radio access network benchmark," 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 11 2017. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/04/5G-Xcast_D3.1_v1.1_web.pdf

[57] E. Garro, “Air interface,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 07 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_WP3_D3.2_v3.00_web.pdf

[58] M. Säily, “Rat logical architecture and interfaces for 5g-xcast,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 02 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/03/5G-Xcast_D3.3_v2.0_web.pdf

[59] F. Tesema, “Rat protocols and radio resource management in 5g-xcast,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 07 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_WP3_D3.4_v3.0.pdf

[60] D. Mi, “Test-beds integration and deployment,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 02 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/04/5G-Xcast_D6.3_v1.0_web.pdf

[61] J. J. Gimenez, “Final evaluation and validation,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 05 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/08/5G-Xcast_D6.4_v2.0_web.pdf

[62] T. Stevens, “Key technologies for the content distribution network,” 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 08 2018. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/07/5G-Xcast_D5.2_v3.0_web.pdf

[63] D. Minoli, *Multicast Listener Discovery*, 2008, pp. 215–233.

[64] A. M. Sulaiman, B. M. Ali, S. Khatun, and G. Kurup, “An enhanced ipv6 anycast routing protocol using protocol independent multicast-sparse mode (pim-sm),” in *2007 IEEE International Conference on Telecommunications and Malaysia International Conference on Communications*, 2007, pp. 588–593.

[65] Säily, Mikko and Barjau, Carlos and Navratil, David and Prasad, Athul and Gomez-Barquero, David and Tesema, Fasil B., “5g radio access networks: Enabling efficient point-to-multipoint transmissions,” *IEEE Vehicular Technology Magazine*, vol. 14, no. 4, pp. 29–37, 2019.

[66] G. Masini, *A Guide to NG-RAN Architecture.* Springer International Publishing, 2021, ch. 8, pp. 233–258. [Online]. Available: https://doi.org/10.1007/978-3-030-58197-8_8

[67] C. Menzel, "Analysis and deployment of terrestrial broadcast in 5g-xcast," 5G-Xcast. Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems, Deliverable, 05 2019. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/08/5G-Xcast_D2.4_v2.0_web.pdf

[68] C. Barjau, M. Säily, and D. G. Barquero, "Enabling sfn transmissions in 5g cloud-ran deployments," in *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, 2019, pp. 1–5.

[69] 3GPP, "NG-RAN; F1 Application Protocol (F1AP)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 26.850, 09 2022, version 17.2.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3260

[70] P. Marques, J. Rodriguez, T. Forde, L. Doyle, K. W. Sung, J. Lauterjung, and U. H. Reimers, *Towards a Unified 5G Broadcast-Broadband Architecture.* John Wiley & Sons, Ltd, 2015, ch. 8, pp. 191–206. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118867464.ch8

[71] K. Edelman, "Digital media trends survey 12th edition. a new world of choice for digital consumers," Deloitte Insights, Survey, 12 2018. [Online]. Available: https://www2.deloitte.com/content/dam/insights/us/articles/4479_Digital-media-trends/4479_Digital_media%20trends_Exec%20Sum_vFINAL.pdf

[72] S. Ahn, S.-I. Park, J.-Y. Lee, N. Hur, and J. Kang, "Cooperation between ldm-based terrestrial broadcast and broadband unicast: On scalable video streaming applications," *IEEE Transactions on Broadcasting*, vol. 67, no. 1, pp. 2–22, 2021.

[73] ETSI, "Mobile broadcast convergence group report," ETSI, Group Report, 6 2018. [Online]. Available: https://www.etsi.org/deliver/etsi_gr/MBC/001_099/001/01.01.01_60/gr_mbc001v010101p.pdf

[74] S. Ilsen, F. Juretzek, L. Richter, D. Rother, and P. BrÃ©tillon, "Tower overlay over lte-advanced+ (tool+): Results of a field trial in paris," in

2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), 2016, pp. 1–6.

[75] J.-y. Lee, S. I. Park, H.-J. Yim, B.-m. Lim, S. Kwon, S. Ahn, N. Hur, and H. M. Kim, "Atsc 3.0 and lte cooperation for ldm and shvc based mobile broadcasting," in *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, 2019, pp. 1–2.

[76] T. Lohmar and M. Elisova, "Evaluation of the file repair operations for multicast/broadcast download deliveries," in *11th European Wireless Conference 2005 - Next Generation wireless and Mobile Communications and Services*, 2006, pp. 1–6.

[77] D. Lecompte and F. Gabin, "Evolved multimedia broadcast/multicast service (embms) in lte-advanced: overview and rel-11 enhancements," *IEEE Communications Magazine*, vol. 50, no. 11, pp. 68–74, 2012.

[78] T. Schierl, T. Stockhammer, and T. Wiegand, "Mobile video transmission using scalable video coding," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 17, no. 9, pp. 1204–1217, 2007.

[79] S. Kunić and Z. Šego, "Analysis of the hybrid broadcast broadband television standard - hbbtv," in *2019 International Symposium ELMAR*, 2019, pp. 89–92.

[80] 3GPP, "3gpp system to wireless local area network (wlan) interworking; system description," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 23.234, 03 2017. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=824

[81] Wi-fi and cellular convergence - what's new in 5g. [Online]. Available: https://www.aptilo.com/news/blog/wi-fi-and-cellular-convergence-whats-new-in-5g/

[82] 5g: focus on n3iwf, tngf, twif and w-5gan. [Online]. Available: https://romars.tech/pubblicazioni/n3iwf/

[83] 3GPP, "Study on access traffic steering, switch and splitting support in the 5g system (5gs) architecture," 3rd Generation Partnership Project (3GPP), Technical Report (TR) TS 23.793, 12 2018. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3254

[84] ——, “5g system;access traffic steering, switching and splitting (atsss); stage 3,” 3rd Generation Partnership Project (3GPP), Technical specification (TS) TS 24.193, 06 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3607

[85] S. Barré, “Implementation and assessment of modern host-based multipath solutions,” Ph.D. dissertation, UniversitÃ© catholique de Louvain, 2011.

[86] Hitachi, “ATSC 3.0 Overview,” White Paper, Hitachi Kokusai Electric Comark LLC, Apr. 2017.

[87] M. Aitken. (2019, Jun.) ATSC 3.0 (5G Broadcast?) Broadcast / Broadband Convergence. BMSB 2019. Sinclair Broadcast Group.

[88] ATSC, “A/324. scheduler / studio to transmitter link,” Advanced Television Systems Committee, Standard, 3 2022. [Online]. Available: https://muygs2x2vhb2pjk6g160f1s8-wpengine.netdna-ssl.com/wp-content/uploads/2022/06/A324-2022-06-Scheduler-STL.pdf

[89] G. Mayer, “Restful apis for the 5g servicebased architecture,” *Journal of ICT Standardization*, vol. 6, pp. 101–116, 01 2018.

[90] 3GPP, “5g system; network exposure function northbound apis; stage 3,” 3rd Generation Partnership Project (3GPP), Technical specification (TS) TS 29.522, 09 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3437

[91] Atsc 3.0 declared ’ready for deployment. [Online]. Available: https://www.lightreading.com/video/video-services/atsc-30-declared-ready-for-deployment-/d/d-id/750716

[92] 3GPP, “Access to the 3gpp 5g core network (5gcn) via non-3gpp access networks,” 3rd Generation Partnership Project (3GPP), Technical specification (TS) TS 24.502, 06 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3371

[93] J. Iyengar and M. Thomson, “QUIC: A UDP-Based Multiplexed and Secure Transport,” RFC 9000, May 2021. [Online]. Available: https://www.rfc-editor.org/info/rfc9000

[94] IETF, “Multicast Extension for QUIC,” Internet Engineering Task Force, Internet-Draft draft-jholland-quic-multicast-02, 07 2022. [Online]. Available: https://datatracker.ietf.org/doc/draft-jholland-quic-multicast/02/

[95] ——, “Multipath Extension for QUIC,” Internet Engineering Task Force, Internet-Draft draft-ietf-quic-multipath-02, 07 2022. [Online]. Available: https://datatracker.ietf.org/doc/draft-ietf-quic-multipath/02/

[96] 3GPP, “ Feasibility study on new services and markets technology enablers for network operation; Stage 1,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 22.864, 09 2016, version 15.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3016

[97] ——, “ NR Multicast and Broadcast Services,” 3rd Generation Partnership Project (3GPP), Work Item Description (WID) RP-220428, 03 2020. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3016

[98] ——, “Study on architectural enhancements for 5G multicast-broadcast services,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 23.757, 03 2021, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3621

[99] ——, “Study on architectural enhancements for 5G multicast-broadcast services Phase 2,” 3rd Generation Partnership Project (3GPP), Study Item (SI) SP-220072, 06 2020. [Online]. Available: http://www.3gpp.org/ftp/tsg_sa/TSG_SA/TSGS_95E_Electronic_2022_03/Docs//SP-220072.zip

[100] ——, “ Study on Security Aspects of Enhancements for 5G Multicast-Broadcast Services,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 33.850, 12 2021, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3762

[101] ——, “ Multicast Architecture Enhancement for 5G Media Streaming,” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 26.802, 06 2021, version 17.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3740

[102] A. Rico-Alvarino, I. Bouazizi, M. Griot, P. Kadiri, L. Liu, and T. Stockhammer, “3gpp rel-17 extensions for 5g media delivery,” *IEEE Transactions on Broadcasting*, vol. 68, no. 2, pp. 422–438, 2022.

[103] 3GPP, “ 5G Multicast-Broadcast User Service Architecture,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 26.502, 06 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3916

[104] ——, “5G Multicast-Broadcast User Services; Protocols and Formats,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 26.517, 06 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=4018

[105] ——, “Architectural enhancements for 5G multicast-broadcast services,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 23.757, 06 2022, version 17.3.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3854

[106] ——, “NR; NR and NG-RAN Overall description; Stage-2,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 38.300, 07 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3191

[107] ——, “Nr; radio resource control (rrc); protocol specification,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 38.331, 07 2022. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3197

[108] Proyecto campus 5g. [Online]. Available: https://vlc-campus5g.com/

[109] European regional development fund. [Online]. Available: https://ec.europa.eu/regional_policy/en/funding/erdf/

[110] Airscale mmwave radio, deliver extreme 5g capacity. [Online]. Available: https://www.nokia.com/networks/mobile-networks/airscale-radio-access/mmwave-radio/

[111] Ford implanta el 5g en su planta de valencia para gestionar los vehÃculos de guiado automÃ¡tico.

[112] P. Maurice, “Project communications strategy and plan,” GÃ‰ANT Association, Deliverable D2.1, 07 2019. [Online]. Available: https://geant.org/wp-content/uploads/2021/11/D2-1_Project-Communications-Strategy-and-Plan.pdf

[113] Cumucore. the software to build a mobile private network. [Online]. Available: https://cumucore.com/mobile-private-network/

[114] Open5gcore - 5g core network for research, testbeds and trials. [Online]. Available: https://www.open5gcore.org/

[115] Openairinterface, the fastest growing community and software assets in 5g wireless. [Online]. Available: https://openairinterface.org/

[116] srsran, your own mobile network. [Online]. Available: https://www.srsran.com/

[117] free5GC, Link the World! [Online]. Available: https://www.free5gc.org/

[118] Landslide core network testing. [Online]. Available: https://www.spirent.com/products/core-network-test-5g-lte-ims-wifi-diameter-landslide

[119] Mx104 universal routing platform. [Online]. Available: https://www.juniper.net/us/en/products/routers/mx-series/mx204-universal-routing-platform.html

[120] Superserver 1029p-wtrt. [Online]. Available: https://www.supermicro.com/products/system/1U/1029/SYS-1029P-WTRT.cfm

[121] Proxmox virtual environment. [Online]. Available: https://www.proxmox.com/en/proxmox-ve

[122] A. Ibanez, J. Sanchez, D. Gomez-Barquero, J. Mika, S. Babel, and K. Kuehnhammer, “5g broadcast sdr open source platforms,” in *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, 2022, pp. 01–06.

[123] Ettus research products. [Online]. Available: https://www.ettus.com/all-products/ub210-kit/

[124] H.-C. Chang, B.-J. Qiu, C.-H. Chiu, J.-C. Chen, F. J. Lin, D. de la Bastida, and B.-S. P. Lin, “Performance evaluation of open5gcore over kvm and docker by using open5gmtc,” in *NOMS 2018 - 2018 IEEE/IFIP Network Operations and Management Symposium*, 2018, pp. 1–6.

[125] P. Chakraborty, M. Corici, and T. Magedanz, “A comparative study for time series forecasting within software 5g networks,” in *2020 14th International Conference on Signal Processing and Communication Systems (ICSPCS)*, 2020, pp. 1–7.

[126] M. Corici, P. Chakraborty, T. Magedanz, A. S. Gomes, L. Cordeiro, and K. Mahmood, “5g non-public-networks (npn) roaming architecture,” in *2021 12th International Conference on Network of the Future (NoF)*, 2021, pp. 1–5.

[127] K. Mahmood, “Technical blueprint for vertical use cases and validation framework,” FUDGE-5G. FUlly DisinteGrated private nEtworks for 5G verticals, Deliverable D1.1, 02 2021. [Online]. Available: https://fudge-5g.eu/download-file/493/zIrbJ2b9meNEGKKXwkEV

[128] A. Nakao, “Slice components design - ver 1.0,” 5G!PAGODA. A network slice for every service, Deliverable D3.1, 08 2017. [Online]. Available: https://5g-pagoda.aalto.fi/assets/demo/attachement/delivrables/5G!Pagoda%20-%20D3.1%20-%20Slice%20Components%20Design.pdf

[129] P. Lundh, “Preliminary use case specification for transportation services,” 5G-VICTORI. VertIcal demos over Common large-scale field Trials fOr Rail, energy and media Industries, Deliverable D3.1, 07 2021. [Online]. Available: https://www.5g-victori-project.eu/wp-content/uploads/2021/09/2021-07-31-5G-VICTORI_D3.1-Prel-Test-Cases-for-Trp-Services_v1.0.pdf

[130] M. Skarp, “Fudge-5g converged 5glan with tsn and multicast capabilities,” FUDGE-5G. FUlly DisinteGrated private nEtworks for 5G verticals, Deliverable D2.3, 06 2022. [Online]. Available: https://fudge-5g.eu/download-file/493/zIrbJ2b9meNEGKKXwkEV

[131] L. Maknavicius, “Final architecture and deployment results: Achieved results in the final architecture, technologies and infrastructure deployment,” 5G-TOURS.5G smarT mObility, media and e-health for toURists and citizenS, Deliverable D3.4, 12 2021. [Online]. Available: http://5gtours.eu/documents/deliverables/D3.4.pdf

[132] 3GPP, “General packet radio system (gprs) tunnelling protocol user plane (gtpv1-u),” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) TS 29.281, 03 2021. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=1699

[133] iftop(8) - linux man page. [Online]. Available: https://linux.die.net/man/8/iftop

[134] Qemu/kvm virtual machines. [Online]. Available: https://pve.proxmox.com/wiki/Qemu/KVM_Virtual_Machines

[135] Open software toolbox for connected media applications. [Online]. Available: https://www.5g-mag.com/reference-tools

[136] D. Vargas and Y. J. D. Kim, "Two-layered superposition of broadcast/multicast and unicast signals in multiuser ofdma systems," *IEEE Transactions on Wireless Communications*, vol. 19, no. 2, pp. 979–994, 2020.

[137] J. J. Gimenez, D. Gomez-Barquero, J. Morgade, and E. Stare, "Wideband broadcasting: A power-efficient approach to 5g broadcasting," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 119–125, 2018.