Broadcasting in 4G mobile broadband networks and its evolution towards 5G

A thesis for the degree of
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Als meus pares, als meus germans i a Clara.

Abstract

One of the challenges of the mobile industry is to cope with the growth of mobile traffic demand expected for the next years, primarily driven by the increasing usage of mobile video services. Indeed, the existence of increasingly powerful terminals is encouraging the consumption of high-quality video content. Usually, video services are identified with linear Television (TV) and scheduled broadcast (point-to-multipoint (p-t-m)) distribution. However, the consumption of video content over mobile networks is different from traditional fixed TV because contents are mainly consumed on-demand with unicast point-to-point (p-t-p) connections. Then, the convergence of linear TV and on-demand content delivery represents a challenge that requires a combined broadcast/unicast transmission model.

This dissertation addresses the use of broadcasting technologies for the provision of mobile multimedia services in Fourth Generation (4G) mobile broadband networks and beyond. Specifically, the dissertation focuses on the broadcast technology included in 4G Long Term Evolution (LTE) and LTE Advanced (LTE-A) networks, known as Evolved Multimedia Broadcast Multicast Services (eMBMS). It analyses the benefits of the eMBMS physical layer aspects regarding Multimedia Broadcast Multicast Services over Single Frequency Network (MBSFN) deployments and identifies the current limitations of eMBMS at physical layer by comparing with the broadcast technology of the other 4G mobile system, the IEEE 802.16m standard. Those limitations are the use of a dedicated carrier and Multiple-Input Multiple-Output (MIMO) techniques for broadcast transmissions. Our investigations employ a complete simulation platform including link-level and system-level simulations to evaluate the performance of broadcast transmissions in these real technologies.

The research on eMBMS services is aimed at finding the optimum delivery of streaming and file download services focusing on the Radio Resource Management (RRM) problem and trade-off between Physical layer - Forward Error Correction (PHY-FEC) and Application Layer - Forward Error Correction (AL-FEC). Concerning streaming services, results show that the use of

AL-FEC increases the coverage level and, then, the maximum service data rate. The gain due to AL-FEC is greater in scenarios with high mobility users, although, this gain is limited if low zapping times are desired. Regarding file delivery services, this dissertation analyses the duration of the transmission required to guarantee the correct file reception and the reduction in the mean throughput of unicast users with different delivery modes. They are the unicast delivery, the eMBMS delivery and a hybrid approach, which combines a first eMBMS delivery with a post-delivery error repair phase with unicast transmissions. Our results show that the hybrid delivery is the most efficient configuration in terms of file download time, although it further reduces unicast performance.

On the other hand, as an exemplary use case, this dissertation also investigates the use of LTE networks for the provision of vehicular safety services comparing both unicast and eMBMS delivery modes. Results highlight the significant benefits in terms of resource usage, end-to-end latency and cost delivery saving that can be achieved by using eMBMS for the delivery of road safety applications. In addition, research also addresses the problem associated with the support of road safety applications over the current eMBMS architecture, the configuration of the Intelligent Transportation Systems (ITS) server in charge of distributing safety messages as well as on its interaction with the mobile network operator.

Finally, this dissertation analyzes feasible options of convergence between mobile and broadcast industry to ensure the success of the mobile broadcasting deployments in the future. A separated evolution of the broadcast technologies of both industries would lead to a scenario with two complete different industries, with different network infrastructures and business models competing for market and spectrum. This dissertation proposes an approach by which the definition of the future Fifth Generation (5G) mobile broadband communication system could bring together the cellular and broadcast industries to form a single fixed and mobile converged network and offer a full alternative to terrestrial TV broadcasting as a universal service.

Resumen

Uno de los desafíos de la industria móvil es hacer frente al aumento de la demanda de tráfico móvil esperado para los próximos años, impulsado principalmente por el uso creciente de los servicios de vídeo para móviles. Ciertamente, la existencia de terminales cada vez más potentes está alentando el consumo de contenido de vídeo de alta calidad. A menudo, los servicios de vídeo se identifican con la radiodifusión programada de los servicios de TV lineal utilizando la distribución punto a multipunto (*broadcast*). Sin embargo, el consumo de contenido vídeo sobre las redes móviles es diferente de la TV fija tradicional ya que los contenidos se consumen principalmente bajo demanda del usuario con conexiones punto a punto (*unicast*). Por lo tanto, la convergencia de la distribución de TV lineal y contenido bajo demanda representa un desafío que requiere un modelo que combine ambos tipos de transmisiones, *broadcast* y punto a punto *unicast*.

Esta tesis doctoral aborda el uso de las tecnologías de radiodifusión para la provisión de los servicios multimedia a dispositivos móviles en las redes de banda ancha móvil de cuarta generación (4G) y su evolución más allá de 4G. Específicamente, la tesis se centra en la tecnología de radiodifusión incluida en las redes 4G LTE y LTE-Advanced, conocida como eMBMS. Se analizan los beneficios de los aspectos de la capa física de eMBMS con respecto a los despliegues de redes de radiodifusión sincronizadas en tiempo y frecuencia (MBSFN) y se identifican las limitaciones actuales de la capa física de eMBMS comparando con la tecnología de radiodifusión del otro sistema celular 4G como es el estándar IEEE 802.16m. Esas limitaciones son el uso de portadoras dedicadas y de técnicas con múltiples antenas en transmisión para la distribución *broadcast*. Nuestras investigaciones emplean una plataforma completa de simulación que incluye simulaciones a nivel de enlace y a nivel de sistema para evaluar las prestaciones de la radiodifusión en esas tecnologías reales.

La investigación sobre los servicios eMBMS está encaminada en encontrar la transmisión óptima de los servicios de *streaming* de vídeo y descarga de ficheros centrándose en el problema de la gestión de los recursos radio y la solución de compromiso entre las técnicas de corrección de errores en la capa física (PHY-FEC) y la de aplicación (AL-FEC). Respecto a los servicios de *streaming* de vídeo, los resultados muestran que el uso de mecanismos de corrección de errores en la capa de aplicación aumenta el nivel de cobertura y, por lo tanto, la máxima velocidad de transmisión de los datos del servicio. La ganancia debido al uso de AL-FEC es mayor en escenarios con usuarios de alta movilidad, aunque esta ganancia está limitada si se desea tener tiempos de zapeo bajos. Respecto a los servicios de descarga de ficheros, esta tesis analiza la duración de la transmisión requerida para garantizar la correcta recepción del fichero y la reducción de la velocidad de transmisión de los datos media en los usuarios *unicast* con diferentes modos de transmisión. Los modos de transmisión son la entrega mediante *unicast*, eMBMS y un método híbrido que combina una primera fase con eMBMS y una fase posterior de corrección de errores con transmisiones *unicast*. Nuestros resultados muestran que este último modo es la configuración más eficiente en términos de tiempo de descarga del fichero, aunque se reducen más las prestaciones de los usuarios *unicast*.

Por otra parte, como un ejemplo de caso de uso, esta tesis doctoral también investiga el uso de las redes LTE para la provisión de los servicios de seguridad vehiculares comparando los modos de transmisión *unicast* y eMBMS. Los resultados resaltan que con el uso de eMBMS para la provisión de las aplicaciones de seguridad en carretera se pueden alcanzar significantes beneficios en términos de uso de recursos, latencia extremo a extremo y el ahorro en el coste de transmisión. Además, la investigación también aborda el problema asociado con el soporte de estas aplicaciones en la actual arquitectura de eMBMS, la configuración del servidor de los sistemas de transporte inteligente (ITS) encargado de distribuir los mensajes de seguridad así como su interacción con el operador de red móvil.

Finalmente, esta tesis doctoral analiza las posibles opciones de convergencia entre la industria móvil y los radiodifusores de TV digital terrestre para asegurar el éxito de los despliegues de redes de radiodifusión móvil en el futuro. Una evolución separada de las tecnologías de radiodifusión de ambas industrias llevaría a un escenario con dos industrias diferentes, con sus diferentes infraestructuras de red y modelos de negocio, compitiendo por el mercado y espectro. Esta tesis doctoral propone una estrategia basada en que la futura definición del sistema de comunicaciones de banda ancha móvil de quinta generación (5G) junte la industria móvil y la de radiodifusión para formar una única red convergente fija y móvil. Esto permitiría ofrecer una alternativa completa para que la radiodifusión de TV terrestre sea un servicio universal.

Resum

Un dels desafiaments de la indústria mòbil és fer front a l'augment de la demanda de tràfic mòbil esperat per als propers anys, impulsat principalment per l'ús creixent dels serveis de vídeo per a mòbils. Certament, l'existència de terminals cada volta més potents està fomentant el consum de contingut de vídeo d'alta qualitat. Sovint, els serveis de vídeo s'identifiquen amb la radiodifusió programada dels serveis de televisió lineal utilitzant la distribució punt a multipunt (*broadcast*). No obstant això, el consum de contingut vídeo sobre les xarxes mòbils és diferent de la televisió fixa tradicional ja que els continguts es consumeixen principalment sota demanda de l'usuari amb connexions punt a punt (*unicast*). Per tant, la convergència de la distribució de televisió lineal i contingut sota demanda representa un desafiament que requereix un model que combine ambdós tipus de transmissions, *broadcast* i punt a punt *unicast*.

Aquesta tesi doctoral aborda l'ús de les tecnologies de radiodifusió per al proveïment dels serveis multimèdia a dispositius mòbils en les xarxes de banda ampla mòbil de quarta generació (4G) i la seua evolució més enllà de 4G. Específicament, la tesi es centra en la tecnologia de radiodifusió inclosa en les xarxes 4G LTE i LTE-Advanced, coneguda com eMBMS. S'analitzen els beneficis dels aspectes de la capa física d'eMBMS pel que fa als desplegaments de xarxes de radiodifusió sincronitzades en temps y freqüència (MBSFN) i s'identifiquen les limitacions actuals de la capa física d'eMBMS comparant amb la tecnologia de radiodifusió de l'altre sistema cel·lular 4G com és l'estàndard IEEE 802.16m. Aquestes limitacions són l'ús de portadores dedicades i de tècniques amb múltiples antenes en transmissió per a la distribució *broadcast*. Les nostres investigacions fan servir una plataforma completa de simulació que inclou simulacions a nivell d'enllaç i a nivell de sistema per avaluar les prestacions de la radiodifusió amb eixes tecnologies reals.

La investigació sobre els serveis eMBMS es centra en trobar la transmissió òptima dels serveis d'*streaming* de vídeo i descàrrega de fitxers centrant-se en el problema de la gestió dels recursos radio i la solució de compromís entre les tècniques de correcció d'errors a la capa física (PHY-FEC) i la d'aplicació

(AL-FEC). Respecte als serveis d'*streaming* de vídeo, els resultats mostren que l'ús de mecanismes de correcció d'errors a la capa d'aplicació augmenta el nivell de cobertura i, per tant, la màxima velocitat de transmissió de les dades del servei. El guany degut a l'ús d'AL-FEC és major en escenaris amb usuaris d'alta mobilitat, encara que aquest guany està limitat si es desitja tenir temps de zàping baixos. Pel que fa als serveis de descàrrega de fitxers, aquesta tesi analitza la durada de la transmissió requerida per a garantir la correcta recepció del fitxer i la reducció de la velocitat de transmissió de les dades mitjana en els usuaris *unicast* amb diferents modes de transmissió. Els modes de transmissió són l'entrega mitjançant *unicast*, eMBMS i un mètode híbrid que combina una primera fase amb eMBMS i una darrera fase de correcció d'errors amb transmissions *unicast*. Els nostres resultats mostren que aquest últim mode és la configuració més eficient en termes de temps de descàrrega del fitxer, encara que es redueixen més les prestacions dels usuaris *unicast*.

D'altra banda, com un exemple de cas d'ús, aquesta tesi doctoral també investiga l'ús de las xarxes LTE per al proveïment dels serveis de seguretat vehiculars comparant els modes de transmissió *unicast* i eMBMS. Els resultats ressalten que amb l'ús d'eMBMS per al proveïment d'aplicacions de seguretat en carretera es poden aconseguir significants beneficis en termes d'ús de recursos, latència extrem a extrem i estalvi en el cost de transmissió. A més, la investigació també aborda el problema associat amb el suport d'aquestes aplicacions en l'actual arquitectura d'eMBMS, la configuració del servidor dels sistemes de transport intel·ligent (ITS) encarregat de distribuir els missatges de seguretat així com la seua interacció amb l'operador de xarxa mòbil.

Finalment, aquesta tesi analitza les possibles opcions de convergència entre la indústria mòbil i els radiodifusors de TV digital terrestre per assegurar l'èxit dels desplegaments de xarxes de radiodifusió mòbil en el futur. Una evolució separada de les tecnologies de radiodifusió d'ambdues indústries donaria lloc a un escenari amb dos indústries diferents, amb les seues diferents infraestructures de xarxa i models de negoci, competint pel mercat i espectre. Aquesta tesi doctoral proposa una estratègia basada en que la futura definició del sistema de comunicacions de banda ampla mòbil de cinquena generació (5G) junte la indústria mòbil i la de radiodifusió per a formar una única xarxa convergent fixa i mòbil. Açò permetria oferir una alternativa completa per a que la radiodifusió de TV terrestre siga un servei universal.

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Jordi Calabuig Gaspar
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List of Acronyms

2G	Second Generation
3G	Third Generation
3GP-DASH	Progressive Download and Dynamic Adaptive Streaming over HTTP
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
4G	Fourth Generation
5G	Fifth Generation
AL-FEC	Application Layer - Forward Error Correction
ALC	Asynchronous Layered Coding
ARQ	Automatic Repeat request
ARP	Allocation and Retention Priority
AS	Access Stratum
ATSC	Advanced Television Systems Committee
ATSC 3.0	Advanced Television Systems Committee 3.0
AU	Application Unit
AVC	Advanced Video Coding
AWGN	Additive White Gaussian Noise
BCCH	Broadcast Control Channel

BCH Broadcast Channel

BER Bit Error Rate

BLER Block Error Rate

BM-SC Broadcast Multicast - Service Center

BS Base Station

C-ITS Cooperative Intelligent Transport Systems

CA Cooperative Awareness

CAM Cooperative Awareness Message

CAPEX Capital Expenditures

CBS Common Broadcast Specification

CCCH Common Control Channel

CCU Communication and Control Unit

CEN European Committee for Standardization

CN Core Network

CP Cyclic Prefix

CPHY Common Physical Layer

CR Code Rate

CRC Cyclic Redundancy Check

CS Circuit-Switched

CSI Channel State Information

CQI Channel Quality Indicator

CRC Cyclic Redundancy Check

CSA Common Subframe Allocation

CSI Channel State Information

DASH Dynamic Adaptive Streaming over HTTP

DCCH Dedicated Control Channel

DENM Decentralized Environmental Notification Message

DL-SCH Downlink Shared Channel

DNS Domain Name System

DMB Digital Multimedia Broadcasting

DTCH Dedicated Traffic Channel

DTMB Digital Terrestrial Multimedia Broadcast

DTT Digital Terrestrial Television

DVB Digital Video Broadcasting Project

DVB-H Digital Video Broadcasting – Handheld

DVB-NGH Digital Video Broadcasting - Next Generation Handheld

DVB-T2 Digital Video Broadcast - Terrestrial 2nd Generation

eMBMS Evolved Multimedia Broadcast Multicast Services

E-MBS Enhanced Multicast and Broadcast Services

eNB evolved Node B

EPA Extended Pedestrian A

EPC Evolved Packet Core

EPS Evolved Packet System

ESI Encoded Symbol ID

ESM Effective SINR Mapping

ESR Erroneous Second Ratio

ETU Extended Typical Urban

ETSI European Telecommunications Standards Institute

E-UTRA Evolved Universal Terrestrial Radio Access

E-UTRAN Evolved Universal Terrestrial Radio Access Network

EVA	Extended Vehicular A
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FEF	Future Extension Frame
FFT	Fast Fourier Transform
FLUTE	File Delivery over Unidirectional Transport
FOBTV	Future of Broadcast Television
HARQ	Hybrid ARQ
HDTV	High Definition Television
HEVC	High Efficiency Video Coding
HPHT	High Power High Tower
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSPA+	Evolved High-Speed Packet Access
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IMB	Integrated Mobile Broadcast
IMT	International Mobile Telecommunications
IMT-Advanced	International Mobile Telecommunications - Advanced
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6

IP PER Internet Protocol Packet Error Ratio

ISD Inter-Site Distance

ISDB Integrated Services Digital Broadcasting

ISI Inter-symbol Interference

ITS Intelligent Transportation Systems

ITS-G5 ITS Frequency band 5.9 GHz dedicated for safety related applications

ITU International Telecommunication Union

L1 Layer 1

L2S Link-to-System

LCT Layered Coding Transport

LDM Layer Division Multiplexing

LPLT Low Power Low Tower

LTE Long Term Evolution

LTE-A LTE Advanced

LUT Look-Up Tables

M2M Machine-to-machine

M^3 Mobile Multi-Media

MAC Medium Access Control

MBMS Multimedia Broadcast Multicast Service

MBMS GW Multimedia Broadcast Multicast Services Gateway

MBSFN Multimedia Broadcast Multicast Services over Single Frequency Network

MCCH Multicast Control Channel

MCE Multicell Coordination Entity

MCH Multicast transport Channel

MCS	Modulation and Coding Scheme
MI	Mutual Information
MIB	Master Information Block
MIESM	Mutual Information Effective SINR Mapping
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
MNO	Mobile Network Operator
MRB	MBSFN Radio Bearer
MRC	Maximum Ratio Combining
MSA	MCH Subframe Allocation
MSI	MCH Scheduling Information
MSP	MCH Scheduling Period
MTCH	Multicast Traffic Channel
MTU	Maximum Transmission Unit
NAS	Non-Access Stratum
NCT	New Carrier Type
NAL	Network Abstraction Layer
NCT	New Carrier Type
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
P-GW	PDN Gateway
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel

PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PDCP	Packet Data Convergence Protocol
PDP	Power Delay Profile
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDN	Packet Data Network
PDU	Protocol Data Unit
PER	Packet Error Rate
PHICH	Physical Hybrid ARQ Indicator Channel
PHY	Physical layer
PHY-FEC	Physical layer - Forward Error Correction
PLMN	Public Land Mobile Network
PMCH	Physical Multicast Channel
PMSE	Programme Making and Special Events
PRU	Physical Resource Unit
PS	Packet-Switched
p-t-m	point-to-multipoint
p-t-p	point-to-point
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RACH	Random Access Channel
RAT	Radio Access Technology

RB	Resource Block
RE	Resource Element
RHW	Road Hazard Warning
RLC	Radio Link Control
RMa	Rural Macro-cell
RoHC	Robust Header Compression
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal
RSU	Road Side Unit
RTP	Real-time Transport Protocol
RTT	Round-Trip Time
RX	Reception
S-GW	Serving Gateway
SAE	System Architecture Evolution
SEVA	Simplified Extended Vehicular A
SFN	Single Frequency Network
SI	System Information
SIM	Subscriber Identity Module
SI	Symbol Mutual Information
SIB	System Information Block
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference Plus Noise Ratio
SM	Spatial Multiplexing
SMS	Short Message Service

SNR	Signal-to-Noise Ratio
TBS	Transport Block Size
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
T-DMB	Terrestrial - Digital Multimedia Broadcasting
TMGI	Temporary Mobile Group Identity
TTI	Transmission Time Interval
TV	Television
TX	Transmission
UDP	User Datagram Protocol
UE	User Equipment
UHDTV	Ultra High Definition Television
UHF	Ultra High Frequency
UL-SCH	Uplink Shared Channel
UMa	Urban Macro-cell
UMTS	Universal Mobile Telecommunications System
USA	United States of America
USD	User Service Description
VA	Vehicular A
WAP	Wireless Application Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WRC-07	World Radiocommunication Conference 2007
WRC-15	World Radiocommunication Conference 2015

Chapter 1

Introduction

1.1 Background

The mobile communications sector is characterized by a worldwide rapid increase in traffic demands due to the continuously evolving requirements and expectations of both users and operators. Nowadays, mobile voice service is already considered a commodity by most of mobile users, and mobile data and multimedia services are fast becoming an essential part of consumers' life. In 2014, global mobile data traffic grew 69% and it is expected that it will increase nearly 10-fold between 2014 and 2019 [1], primarily driven by the increasing usage of mobile multimedia services.

Among the different mobile multimedia services, mobile video services are the most representative. As these services have much higher bit rates than other mobile service types, it is expected that mobile video content will generate much of the mobile traffic growth foreseen until 2019. In fact, mobile video represented more than half of global mobile data traffic (55%) in 2014, indicating the needs for solutions to address that video demand today, not just in the future [1]. One of the main keys of the current video demand growth is the success of mobile devices like laptops, tablets and smartphones, which are capable of displaying high-quality video content thanks to their large screen size and high resolution.

Video services are often identified with linear Television (TV) and scheduled broadcast (point-to-multipoint (p-t-m)) distribution. However, the consumption of video content over mobile networks is different from traditional fixed TV because contents are mainly consumed on-demand with unicast (point-to-point (p-t-p)) connections. Then, the convergence of linear TV and on-demand content represents a challenge that requires a combined broadcast/unicast delivery model.

1.1.1 Broadcasting in mobile networks

Traditionally, mobile networks have focused on the transmission of data intended for a single user by employing dedicated p-t-p radio bearers. In this way, consumers have been experiencing the very first steps of multimedia delivery over Third Generation (3G) unicast transmissions. These unicast systems were not designed to address the distribution of popular contents to a large number of users. Conversely, they can easily support a wide diversity of user demands, as each user can ask for a different service or a different instance of the same service with different transmission parameters.

However, the main drawback of unicast delivery is its unfavorable scaling when delivering the same content to many users at the same time. This limits the maximum number of users that cellular systems can handle, since both radio and network resources are scarce. Then, broadcasting is a more appropriate transport technology to cope with a high number of users consuming simultaneously the same service. Mobile broadcast transmissions employ a common p-t-m radio bearer for all users, which allows delivering the same content to an unlimited number of users within the coverage area. Per contra, they cannot support a high number of personalized services and the transmission scheme has to be designed for the worst-case user.

From 3G cellular networks, mobile industry has developed several mobile broadcast technologies to support large-scale consumption of mass multimedia services on mobile devices. In March 2005, Universal Mobile Telecommunications System (UMTS) integrated Multimedia Broadcast Multicast Service (MBMS) as a technical feature in Release 6 [2]. This improvement represented a major development towards the seamless integration of multicast and broadcast technologies into the existing 3G networks. MBMS introduced new p-t-m radio bearers and multicast support in the core network.

In order to boost performance of mobile broadcast transmissions, the Third Generation Partnership Project (3GPP) standardized the use of Multimedia Broadcast Multicast Services over Single Frequency Network (MBSFN) in Release 7 [3]. In Single Frequency Networks (SFNs), multiple base stations are synchronized and transmit at the same frequency the same information to the receivers. This combined transmission allows for an improvement of the signal quality reception, as compared with the non-SFN operation, and hence MBSFN operation increases the efficiency of MBMS service delivery. Later on, 3GPP issued Integrated Mobile Broadcast (IMB) concept in Release 8, which enables spectrally-efficient delivery of multicast and broadcast services in 3G

Time Division Duplex (TDD) bands in a way that is integrated with existing 3G Frequency Division Duplex (FDD) unicast technology [4].

To this date, MBMS has not been incorporated in commercial 3G networks due mainly to the lack of a successful business model. However, the evolution towards Fourth Generation (4G) cellular networks along with the increasing demand of mass multimedia services have regained the interest on the deployment of broadcast technologies in mobile networks.

The 3GPP Long Term Evolution (LTE) standard represents the evolution of the current 3G systems towards 4G and addresses the increasing demand of mobile broadband communications consumers. While current technologies –UMTS, High-Speed Packet Access (HSPA) and Evolved High-Speed Packet Access (HSPA+)– are jointly known as 3G, LTE is a predecessor of 4G technologies and, in fact, the Release 10, known as LTE Advanced (LTE-A), fulfills the requirements established by International Telecommunication Union (ITU) to be considered as 4G technology. LTE was designed from the beginning with the goal of evolving the radio access technologies under the assumption that all services would be packet-switched. Unlike previous technologies, LTE adopted Orthogonal Frequency Division Multiplexing (OFDM) as its radio access technology, which is the one dominating the latest evolutions of all mobile radio standards. This change was accompanied by an evolution of the non-radio aspects of the complete system towards a flat and all-Internet Protocol (IP) system architecture.

The LTE specification ensures peak data rates above 100 Mbps in downlink, minimum peak data rates of 50 Mbps in uplink and Round-Trip Times (RTTs) lower than 10 ms. In addition, LTE can operate in several frequency bands and supports system bandwidth scalable from 1.4 MHz to 20 MHz in FDD and TDD modes. Concerning broadcast provision, LTE includes old features used in previous 3GPP standards (e.g., the use of SFN) and new features inherited from other successful terrestrial broadcast networks such as the use of extended Cyclic Prefix (CP) in order to support MBSFNs. The new broadcast capabilities are referred to as Evolved Multimedia Broadcast Multicast Services (eMBMS) from Release 9 on [5], thus including LTE and LTE-A.

The higher potential of eMBMS with respect to previous MBMS releases together with the increase of video traffic demand have led to the first trials and commercial eMBMS networks in 2014 [6]. As some examples, in January 2014, Verizon Wireless used the Super Bowl in New York as a test case for eMBMS technology and Korea Telecom completed the world's first commercial launch of LTE Broadcast services using eMBMS technology.

1.1.2 eMBMS: the LTE Broadcast mode

According to 3GPP specifications [7], one of the targets of eMBMS is to support a cell-edge spectral efficiency in an urban or suburban environment of 1 bps/Hz, which is equivalent to the support of at least 16 mobile TV channels at around 300 kbps per channel in a 5 MHz carrier [8].

From a technical point of view, the key elements for the successful introduction of eMBMS within LTE networks are, firstly, achieving a good coverage throughout the entire network, especially at the cell-edge, and secondly, reducing device power consumption when receiving eMBMS services. The former can be achieved by exploiting the special features of the OFDM air interface over an MBSFN operation mode. The latter can be done by using a discontinuous reception of eMBMS services, i.e. combining short and high-data-rate bursts with a long period of inactivity.

The initial LTE Release 8 physical layer specifications were already designed to support eMBMS [9]. However, eMBMS discussion was postponed in Release 8 due to the lack of time and, then, higher layer and network architecture aspects were finalized in Release 9 [5]. Moreover, the work on eMBMS has continued within 3GPP and new features and enhancements of eMBMS have been included in 3GPP Releases 10 to 12 [10].

- Physical layer aspects

3GPP specifies that eMBMS services are only supported on a frequency layer shared with unicast services using the MBSFN mode of operation. In MBSFN operation, several time-synchronized cells within a particular area, defined as MBSFN area in LTE, transmit simultaneously the same eMBMS data. Therefore, users observe multiple versions of the same signal with different delays depending on the distance to the evolved Node Bs (eNBs). Figure 1.1 shows an example of an MBSFN area, that is, the group of synchronized cells transmitting the same content at the same frequency. In general, the MBSFN operation entails the following benefits:

- An increase in the received signal level, especially in the border of cells inside the MBSFN area.
- A reduction in the interference level, again especially in the cell borders inside the MBSFN area, since the signals received from neighboring cells do not appear as interference but as constructive signals.
- An additional diversity gain against signal fading, since data are received from different paths.

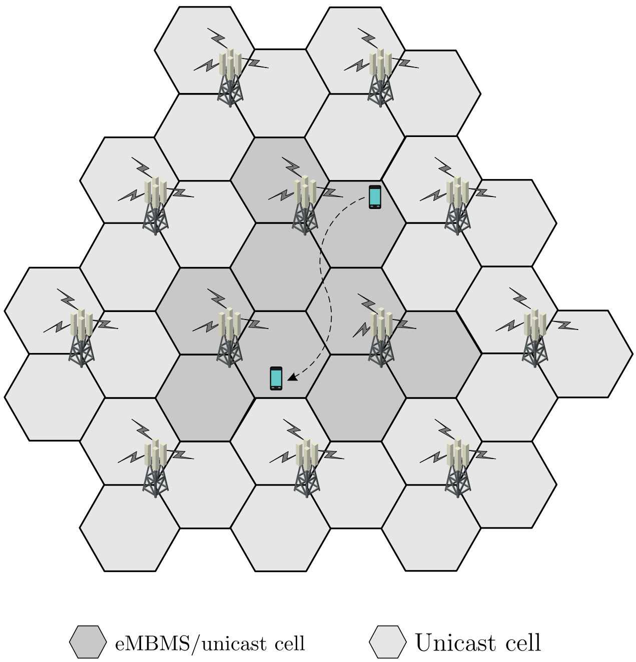

Figure 1.1: An example of an MBSFN area to provide eMBMS services.

With the aim of preserving orthogonality, signals from cells that forms the MBSFN must reach the users within the CP. Otherwise, the signal produces Inter-symbol Interference (ISI). In order to allow for larger MBSFN area sizes, the LTE standard increases the CP from 4.6 μs, called normal CP, to 16.7 μs, which is named extended CP, for the MBSFN physical channel [9]. In addition, an optional double CP length of around 33 μs can be used in scenarios with large Inter-Site Distances (ISDs). In order to avoid an increase in overhead due to the double-sized CP, the core OFDM symbol duration is doubled as well, implying that the number of subcarriers is doubled (by defining subcarrier spacing of 7.5 kHz instead of 15 kHz). The double CP length feature is only available in MBSFN dedicated carrier deployments. However, this configuration is not supported in current releases of LTE and LTE-A. Besides, the pilot pattern is also modified for the MBSFN operation. Pilot signals are closer in the frequency domain as compared with the unicast pattern because the usage of MBSFN implies a reduction in the coherence bandwidth.

On the other hand, one of the most important means to achieve the high data rate objectives for LTE is Multiple-Input Multiple-Output (MIMO) transmission [11]. In LTE downlink it is supported one, two or four transmit antennas at the eNB and one, two or four receive antennas at the User Equipment (UE). In LTE-A, the maximum number of antennas is increased up to eight. Multiple antennas can be used in different ways. When the Signal-to-Noise Ratio (SNR) is high, MIMO can be used to get spatial multiplexing to increase the data rate by creating several parallel channels. For situations with low SNR, it is better to use other types of multi-antenna techniques to obtain additional transmit/receive diversity and improve the SNR.

3GPP has not standardized any MIMO scheme for eMBMS transmissions. Then, eMBMS data are provided using single antenna mode. However, other 4G systems such as Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16m support several MIMO schemes for broadcast transmissions [12].

- eMBMS services delivery

eMBMS standard offers two delivery methods: streaming and file download [13]. In streaming services a continuous data flow of audio, video and subtitling is transmitted to the terminals, and is directly consumed by the users. Occasional data errors are tolerated. In file download services a certain amount of data is delivered and stored into the terminals as a file, which can then be consumed immediately or not. On the contrary to streaming services, file delivery services require an error-free transmission of the files (i.e., even a single bit error corrupts the whole file and makes it useless for the receiver).

Naturally, full reliability cannot be offered in a pure broadcast distribution scheme because the packet loss rate can be excessive for some users. As a solution, 3GPP specifies the usage of Application Layer - Forward Error Correction (AL-FEC) in eMBMS with the aim of increasing the robustness of the p-t-m transmissions. The advantage of AL-FEC is that it can spread the protection over large portions of information. AL-FEC takes advantage of the temporal diversity derived from user mobility by the use of extensive time interleaving, which increases the robustness of the transmitted information against fast fading and especially, against shadowing and signal outages. Despite having an excellent performance, the main drawback of this approach in streaming delivery is an increase in the channel zapping time, which is considered as a crucial parameter in mobile TV usability. In addition, it is worth noting that the increase of robustness due to the use of AL-FEC entails a reduction on the data rate.

3GPP selected Raptor coding for the AL-FEC [13]. Raptor codes are a computationally efficient implementation of fountain codes that achieve close to ideal performance, and allow for a software implementation without the need of dedicated hardware even in handheld devices [14]. They are very suitable for data delivery –streaming and file download– in wireless broadcast systems when working at the application layer, outperforming other Forward Error Correction (FEC) solutions in terms of implementation complexity, spectrum efficiency and flexibility. The main benefits of working at the application layer are that it is possible to recover packet losses of all underlying layers and protocols, providing end-to-end error recovery and, no standardization or modification is required below the application layer.

1.1.3 The challenges of mobile broadcasting beyond 4G

- New opportunities in M2M communications

eMBMS is the most efficient mechanism to distribute the same content to many users, and is an important solution to address the increase on global mobile data traffic. This broadcast technology supports a range of use cases: live streaming of video for high-demand content such as live sports and breaking news, background file delivery for popular content (video, music and pictures), software updates and emergency broadcasts.

Aside from the growth of video demand, the mobile traffic increase over the coming years will also be fueled by emerging applications and new use cases associated with communicating machines. Machine-to-machine (M2M) data traffic and internet of things will create more connectivity demands on the network and boost new applications with characteristics and requirements that will differ significantly from those of current human-centric applications.

One of the most interesting M2M applications are related to automotive industry. The latest developments taking place over the past few years in most areas of wireless communication and wireless networks, in combination with the technological development of the automotive industry, have paved the way for a totally new approach to vehicular safety, which integrates multiple equipment and technologies in one autonomous and intelligent vehicle. In this context, the delivery of vehicular safety applications over LTE mobile networks could create new opportunities for eMBMS.

- Cooperation between mobile broadband and broadcast networks

Radio spectrum is a scarce resource that has a considerable economic and social importance. The total spectrum bandwidth requirements for mobile communication systems in the year 2020 are predicted to be 1280 MHz and 1720 MHz for low and high demand scenarios [15], respectively. However, the spectrum bandwidth allocated by International Telecommunication Union

(ITU) for mobile technologies is much lower than these needs: 693 MHz in Region 1 (Europe, Middle East and Africa, and Russia), 723 MHz in Region 2 (Americas) and 749 MHz in Region 3 (Asia and Oceania).

Mobile industry has always been interested in the Ultra High Frequency (UHF) band (470-862 MHz) due to its good propagation characteristics and its wavelength suitable for both indoor reception and integration in small devices. For many decades, this frequency band was used by terrestrial broadcasting technologies to provide analogue TV. Later on, the development of digital broadcasting technologies allowed the introduction of Digital Terrestrial Television (DTT) and the switchover from analogue to DTT, known as digital dividend [16], released a significant amount of spectrum in UHF.

Under a strong pressure from the mobile industry, the ITU decided in the World Radiocommunication Conference 2007 (WRC-07) to allocate the upper part of the UHF band to International Mobile Telecommunications (IMT) technologies. This band ranges from 790 to 862 MHz in Region 1, and from 698 to 790 MHz in Region 2 and Region 3, and requires additional guard bands to avoid interferences between cellular and broadcast technologies. In addition, the worldwide allocation of the 700 MHz band to IMT technologies is on the agenda for the next World Radiocommunication Conference 2015 (WRC-15) [15].

For broadcasters, releasing frequencies for mobile services in many countries where the DTT services have an important penetration will require a costly retune of networks and receiver infrastructures. At the same time, despite broadcast industry can improve the capacity of DTT networks with the introduction of new generation broadcast standards, the access to sufficient UHF spectrum is still essential in maintaining existing DTT networks and enabling service to smartphones and tablets.

In order to solve the problem in broadcasting spectrum, several approaches for cooperation between both mobile broadband and broadcast industry have emerged in recent years [17, 18]. The main goal is to allow the transmission of mass multimedia services to mobile and stationary receivers through the different network infrastructures used by both industries.

1.2 State of the art

There are some open research issues related to the use of broadcasting technologies in 4G mobile networks. This section aims at analyzing the current sate of the art concerning these topics.

1.2.1 Performance evaluation of eMBMS

From 3G cellular networks, broadcasting in mobile networks has been an interesting topic for researchers, however, the higher capacity of LTE and the particular features included in eMBMS [8] has significantly increased that interest.

Rong *et al.* developed several analytical models to assess the performance of the Orthogonal Frequency Division Multiple Access (OFDMA) systems like LTE when carrying TV services [19–21]. Firstly, an analytical model for the coverage and capacity estimation of MBSFN operation mode was proposed in [19]. The authors also investigated the optimum combination of cell range and Modulation and Coding Scheme (MCS) to reach a certain spectral efficiency target. In [20], the authors studied different mobile TV deployment strategies including unicast transmission, single cell p-t-m transmission and MBSFN operation mode. This work analyzes the impact of the provision of TV services on other unicast services, showing that MBSFN is the most suitable solution in terms of throughput degradation. Finally, an enhanced broadcast solution, which consists of dynamically adapting the modulation to the radio conditions of connected TV users, was proposed in [21]. This study shows how to maximize the system capacity through a secondary usage of the SFN resources by elastic traffic. The analysis allows identifying the Erlang regions where the different broadcast solutions are profitable.

Alexiou *et al.* also presented several studies about eMBMS configurations. First of all, they presented in [22] four different approaches for the efficient selection of the MCS in MBSFN transmissions. These approaches cover different needs that could exist in real world like: (1) the assurance of service continuity for the user with lowest Signal-to-Interference Plus Noise Ratio (SINR) value, (2) the selection of the MCS that maximizes the spectral efficiency, (3) the selection of the MCS based on the covered area or (4) the percentage of users that receive the service with acceptable quality. They assessed the impact of this selection on the achieved spectral efficiency taking into account the number and location of users. On the other hand, the same authors performed different studies based on a telecommunication cost analysis of the MBMS service. In [23], the cost analysis of the MBSFN delivery method is based on the transmission cost over the air interface, as well as the costs of all interfaces and nodes of the MBSFN architecture. They considered different network topologies, MBSFN deployments and user distributions. In addition, based on a similar cost analysis, the same authors presented in [24] a complete evaluation study of the eMBMS service provision over a combination of MBSFN and p-t-m transmission methods. This study shows that the proposed selection mechanism is able to provide a cost-efficient transmission session through both transmission schemes in comparison with the other examined methods.

The performance of eMBMS deployments for cell-edge users has also brought attention in the literature [25–28]. On the one hand, the influence of different resource allocation strategies on co-channel interference at the edge of the MBSFN area was analyzed in [25]. The authors proposed an strategy that works well for large MBSFN areas both for slow and static MCS and in the case of fast adaptive MCS based on feedback. In [26], results show that although single-cell eMBMS is more suitable at low user densities, the use of SFNs improves considerably cell-edge rates. The results provided in [27] indicate that the use of soft frequency reuse in MBSFN is essential for improving eMBMS throughput and coverage. Anyway, the lower spectral efficiency at cell-edge motivates the conclusion that eMBMS may not be an efficient solution to offer nationwide contiguous services throughout a mobile network [28]. Those deployments use large ISDs in the vast expanse outside metropolitan and surrounding areas where the eMBMS data rates are low. On the contrary, eMBMS may be efficiently used across an entire metropolitan area and the surrounding rural areas when using a low radio band such as 700 MHz or 800 MHz, offering an impressive spectral efficiency of 1.5 bps/Hz.

Finally, the eMBMS standard has been improved in the LTE-A releases –Release 10 and Release 11–. On the one hand, the eMBMS standard includes in Release 10 a counting procedure [8] to dynamically adapt the transmission of content to the best mode of operation depending on the interested users. Regarding this concept, the user density, which can be determined statistically without explicitly counting the number of users in each cell, together with user feedback are the most convenient criteria for the optimum selection of eMBMS transmission scheme, that is, single-cell eMBMS or MBSFN operation mode [29]. Other authors proposed a genetic algorithm to dynamically configure MBSFN areas according to the distribution of MBMS users [30]. Regarding Release 11, the eMBMS service continuity has been studied in [31], which presents a novel method to ensure the service continuity as well as to reduce the service interruption time during the handover period for eMBMS users in mobility.

1.2.2 eMBMS delivery of streaming and download services

The delivery of streaming and file download services using broadcast transmissions is a well-studied topic in 3G cellular networks. The several studies are mainly focused on the use of AL-FEC protection over broadcast transmissions and the trade-offs between AL-FEC and Physical layer - Forward Error Correction (PHY-FEC).

Regarding file download services, Wang and Zang suggested in [32] that optimal Block Error Rate (BLER) operation points can be used in MBMS. Moreover, this study shows the performance gain of Raptor codes AL-FEC on MBMS coverage, focusing especially on spectrum efficiency and radio resource savings. In addition, Gómez-Barquero *et al.* investigated in [33] the efficient transmission of file download services to several users simultaneously in 3G mobile networks with High-Speed Downlink Packet Access (HSDPA) and MBMS using Raptor coding. They assessed multicast delivery implemented through p-t-p transmissions, a single p-t-m transmission with MBMS or using jointly both of them in a hybrid approach by employing HSDPA for error repair of the MBMS p-t-m initial transmission. Per contra, Azfal *et al.* studied in [34] different system design options for MBMS video streaming over 3G networks and the effect of some parameters related to the AL-FEC configuration on the system performance.

In [35], Stockhammer *et al.* performed a study for both delivery modes. They presented the system trade-offs between AL-FEC and PHY-FEC for MBMS assuming download and streaming services. This study shows that only a well-designed system that properly combines the parameters at the different protocol layers can optimize system resources and user perception. For file delivery, they showed that it is optimum to use less physical layer Turbo code protection and much more application layer Raptor code protection than what was considered in the MBMS standardization process. For streaming delivery, they obtained similar results. However, the protection period must be lower to support the real-time delivery of the service with small channel change times.

There are also several studies in the literature regarding streaming and file download delivery in LTE networks. Alexiou *et al.* assessed FEC for eMBMS file download transmissions based on cost analysis. In [36], the authors proposed a new scheme that takes into account the properties of MBSFN in order to provide a more efficient operation of FEC during eMBMS file delivery transmissions. This scheme uses exclusively the Raptor FEC method for the complete file recovery, which, thanks to transmit redundant information that is necessary to all receivers for the error recovery, outperforms other approaches that selectively transmit lost segments that are probably different among the receivers. In [37], the same authors extended their work studying FEC on the p-t-m transmission mode. In short, they concluded that the total telecommunication cost is strongly related with the network configuration in terms of transmission scheme, MBSFN deployment and error recovery method. Their analysis can define the optimal network configuration that minimizes the total cost based on the distribution of multicast users. On the other hand, Bouras *et al.* studied the application of AL-FEC over the MBMS streaming delivery method over LTE networks in [38]. They assumed a single-cell scenario and investigated how the amount of FEC overhead can be adjusted under different packet loss conditions. They concluded that the necessary overhead is less for pedestrian users than for vehicular users. Moreover, according to their results there is an optimal value of Raptor overhead in terms of the trade-off between transmission redundancy and satisfied users.

In addition, Wang and Zang proposed in [39] a Hybrid ARQ (HARQ) mechanism at the eNB to further improve the reliability provided by AL-FEC in single-cell eMBMS. This study proposes a novel and practical coordination scheme to avoid the unnecessary retransmission and excessive redundancy using both mechanisms, which minimizes the number of transmissions in HARQ by considering the properties of Raptor FEC. Similarly, the trade-off between AL-FEC and HARQ mechanism was analyzed in [40]. The authors presented a probabilistic model to find optimal Raptor encoding rate and number of HARQ retransmissions and results show that it can be achieved a saving of up to 13-15% in network resources compared to existing schemes while ensuring reliable file delivery.

Finally, all these works were performed using 3GPP standardized Raptor coding [13]. However, the emergence of a new variant of Raptor codes, named RaptorQ [41], provides enhanced capabilities for mobile broadcast services. The main goal of these new codes is to minimize the redundant FEC information outperforming Raptor codes. Per contra, the improved coding performance comes at the expense of increased encoding and decoding complexity. Several studies show the higher efficiency of RaptorQ codes with respect to standardized Raptor codes when used in eMBMS transmissions [42–44]. Mladenov *et al.* concluded in [42] that, although the RaptorQ code has excellent coding properties, it is complex for efficient real time decoding in systems like eMBMS. In [43], Bouras *et al.* verified that RaptorQ almost emulates the performance of an ideal FEC code. The minimized required additional data enables RaptorQ operating with significantly lower transmission overhead in comparison to the standardized Raptor FEC. Finally, Kumar and Oyman presented in [44] the superiority of RaptorQ as compared with Raptor codes in terms of rebuffering percentage and quality experienced at the MBMS streaming client.

1.2.3 eMBMS for vehicular communications

The recent advances in wireless communication networks together with the technological development of the automotive industry have paved the way for a totally new approach to vehicular safety, which integrates multiple equipment and technologies in one autonomous and intelligent vehicle. In this context, the term Intelligent Transportation Systems (ITS) [45] refers to a new set of information and communication technologies that allow vehicles to exchange information with each other and with the infrastructure to improve road safety, traffic efficiency and travel comfort.

During 2013, the European Committee for Standardization (CEN) and European Telecommunications Standards Institute (ETSI) finalized a basic set of standards necessary for the implementation and deployment of Cooperative Intelligent Transport Systems (C-ITS) systems as requested by the European Commission [46]. In general, the ITS applications are divided into three main categories that comprise applications with similar requirements [47]: cooperative road safety, cooperative traffic efficiency and cooperative local services and global Internet services. The ITS applications related to cooperative road safety are by far the most challenging ones due to the message frequency and the very stringent latency requirements. For example, the minimum frequency of the periodic messages can be 10 Hz and maximum latency could be less than 100 ms. The two different applications related to cooperative road safety are Cooperative Awareness (CA) and Road Hazard Warning (RHW).

According to CEN and ETSI standards, cooperative road safety communications are based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11p access technology, and are also referred to as ITS-G5 communications by ETSI. The system is well suited to active road safety use cases due to its very low delays and communication range of several hundred meters. However, the channel congestion experienced in dense scenarios and its decentralized ad-hoc nature is motivating the research of other technologies, like cellular networks, as alternatives for ITS communications. The first investigations in this topic began with 3G cellular networks, but more interesting are the studies focusing on the use of LTE cellular networks for vehicular safety applications, due to their better levels of quality in terms of throughput and latency as compared with 3G systems.

In the literature, there is a wide consensus on leveraging the strengths of LTE, such as high capacity, wide coverage and high penetration, to face the main drawbacks of IEEE 802.11p: poor scalability, low capacity and intermittent connectivity. Araniti *et al.* [48] identified some examples where the use of LTE cellular networks for vehicular safety communications is favorable. For CA applications, LTE can be helpful at intersections when IEEE 802.11p communications are obstructed by non-line-of-sight conditions due to buildings. For RHW applications, the wide LTE coverage can be beneficially exploited for the reliable dissemination over large areas of event-triggered safety messages for system scalability and congestion control. Moreover, the benefits of LTE with respect to IEEE 802.11p for vehicular safety communications can be found in [49], where Mir *et al.* evaluated both standards in terms of delay, reliability, scalability, and mobility support under various conditions and parameters settings. Concerning IEEE 802.11p, results show that this standard offers acceptable performance for sparse network topologies and typical transmission frequencies with limited mobility support. By contrast, LTE technology is suitable for most of the applications and use cases although delays increase considerably as the network load increases.

An interesting analysis regarding the applicability of mobile networks to support ITS communications is found in a technical report of ETSI Technical Committee on ITS [50]. In particular, it contains simulation results based on some research projects such as CoCAR [51] and CoCARx [52]. The former focused on 3G cellular networks and analyzed the provision of RHW applications from a technical and commercial point of view. Results show that 3G mobile networks provide the required transmission delay below one second and also the necessary capacity to exchange RHWs. The latter focused on LTE cellular networks and performed a detailed analysis of car-to-car delays and system capacity of 4G networks for vehicular safety applications like CA and RHW. Based on the results for CA applications, the authors did not recommend the use of cellular networks due to the significant load in the mobile network even for low user densities. For RHWs applications, the capacity impact is not as pronounced as for CA applications, thus, the transmission of RHWs over a mobile network is feasible for most of the relevant use cases.

Assuming the use of unicast delivery in cellular networks, results summarized in [50] shows that there is a scalability problem related to the fact that ITS messages have to be delivered to potentially all the vehicles in a certain geographical area with stringent delay requirements. If the unicast transmission mode is used, the amount of resources required for the delivery of ITS messages might result in elevated costs for the Mobile Network Operators (MNOs) as well as for the service providers (e.g. car manufacturers). Then, several studies identify the use of broadcast technologies as a possible solution to tackle the scalability problem of ITS in cellular networks [48, 52, 53].

Most of the studies regarding the capacity of broadcast delivery for vehicular safety communications have been performed in the context of 3G mobile networks [54, 55]. For CA applications, Mangel *et al.* proposed in [53] the use of random access channels in the uplink to prevent underused connections and the use of MBMS in downlink to avoid duplication overhead. Assuming that operation, results show that UMTS is theoretically able to provide 1500 messages per second on one 5 MHz channel. For RHW applications, the use of MBMS is also proposed to efficiently distribute the warning information in areas with a high user density. On the other hand, the use of broadcasting in LTE for vehicular safety applications was studied in [56]. This study proposes the use of broadcast communications from a server to the vehicles to reduce the radio resource usage and control traffic.

1.2.4 Cooperation between mobile broadband and broadcast networks

The topic about cooperation between cellular and broadcasting systems has been studied in past technologies. Gómez-Barquero *et al.* presented several works related to hybrid cellular and broadcasting systems. In [57], they proposed a framework for investigating potential infrastructure cost savings in hybrid cellular and Digital Video Broadcasting – Handheld (DVB-H) systems by performing efficient error repair of broadcast transmissions using AL-FEC. Their main idea is to reuse as much as possible the existing network infrastructure to provide mobile TV services. They concluded that it is possible to reduce the DVB-H infrastructure investment if 3G network is used in the error repair phase. With the same idea, they concluded in [58] that significant savings in transmitted power and number of sites are possible for file download services, even with low amounts of parity data delivered through the cellular system. Related to streaming services, important gains can be achieved as well, at the expense of not providing real-time services everywhere. In addition, they suggested that migrating from linear TV to solutions where content is transmitted during idle times and stored/cached in the terminals, could lead to more cost-efficient ways of realizing mobile TV.

Based on the same technologies, Unger and Kürner presented in [59] an approach for an automatic network planning method of hybrid mobile communication networks combining both unicast and broadcast networks. Their study was based on a reference scenario of Berlin. They concluded that a hybrid network brings benefit to unload the unicast network by providing identical content to many users simultaneously instead of separate transmissions. Besides, Popovic *et al.* compared in [60] the mobile TV network implementation cost between a DVB-H network alone and two types of hybrid DVB-H/3G network. The first hybrid case assumed the 3G network to provide indoor mobile TV signal and DVB-H to outdoor, and the second case is when DVB-H network is composed only of the powerful transmitters of already-existing broadcast infrastructure. They obtained that a significant gain can be achieved using a hybrid network in comparison to a DVB-H network operating alone.

Nowadays, the idea of cooperation between next generation cellular networks and broadcast networks is based on a “Broadcast Overlay”. As shown in several studies, the best way to meet the forecasted explosive growth in mobile data is to allow broadcasters to use p-t-m Broadcast Overlay technology to provide the most efficient possible delivery of high bandwidth data to mobile users. Based on this idea, the study presented in [61] quantifies the superiority of a mobile-friendly Broadcast Overlay service to address growing demand for mobile data and also projects the impact on revenues to the U.S. Treasury from ancillary service fees on broadcasters that provide overlay services.

An example of the benefits of the cooperation between mobile broadband and broadcast networks is presented in [62]. The authors studied the energy consumption in a region where mobile TV is delivered by a standalone LTE network and a standalone Digital Video Broadcasting - Next Generation Handheld (DVB-NGH) transmitter or by a cooperative LTE/Digital Video Broadcasting Project (DVB) network. The cooperation consists in ensuring the mobile TV coverage by DVB in the region surrounding a broadcasting tower and by eMBMS otherwise. Results show that the cooperation decreases the power consumption of at least one of the cooperative operators. Finally, the study presented in [17] consists of proposing features and parameters that could be part of a unified broadcast system specification using 3GPP eMBMS and DVB-NGH. A first set of potential parameters and technologies for such a common physical layer –Common Broadcast Specification (CBS)– are detailed. The main idea is to use the Future Extension Frame (FEF) of Digital Video Broadcast - Terrestrial 2nd Generation (DVB-T2) for the broadcast transmission to mobile terminals.

1.3 Problem formulation

Nowadays, the higher capacity of 4G mobile networks along with the increasing demand on mass multimedia services have regained the interest on the deployment of broadcast technologies in mobile networks. The advantage of LTE in comparison to other broadcast video systems is that the operator has the flexibility to dimension together unicast and broadcast services. Identifying the right mix of services to keep subscribers interested is the real challenge.

With the current state of the technology, eMBMS supports several use cases: those related with live streaming of video for high-demand content, such as live sports and breaking news, and those related to file download delivery such as background file delivery for popular content, software updates and emergency broadcasts.

Several studies on the performance evaluation of eMBMS transmissions for video streaming and file delivery services can be found in literature. Nevertheless, there are some additional interesting issues that must be studied. The main idea is that eMBMS transmissions must be optimally designed in order to maximize the eMBMS system capacity. On the one hand, it is important to explore the benefits of all features introduced in the LTE standard for the transmission of eMBMS services. For instance, MBSFN deployments, optimum MCS selection, scheduling of multimedia services and its effect on unicast users, among others.

In addition, the efficiency of eMBMS can be enhanced. Firstly, it is demonstrated that MIMO schemes improve the capacity of unicast transmissions but these are not supported in eMBMS. The other 4G standard, WiMAX IEEE 802.16m, includes spatial multiplexing schemes and their inclusion within the performance analysis of eMBMS is really appealing. Concerning streaming services, the application of protection techniques at the application layer such as AL-FEC provides to eMBMS transmissions higher protection and flexibility, respectively. So far, the application of these mechanisms to LTE is completely not afforded, and then, there is room for a better performance of streaming services in LTE. With respect to file delivery services, some works have focused on the error recovery to eMBMS transmissions using AL-FEC. However, a post-delivery repair phase employing unicast p-t-p transmissions in LTE eMBMS needs further research.

However, the opportunities of eMBMS extend beyond the video streaming or file download delivery. One of the potential use cases of eMBMS is related to vehicular safety communications. Using unicast transmission mode, the amount of resources required for the delivery of ITS messages might result in elevated costs for the MNOs as well as for the service providers (e.g. car manufacturers). That scalability problem can be solved with the use of eMBMS.

Anyway, the success of mobile broadcast deployments is very much dependent on the availability of spectrum in each country. The terrestrial broadcasting standards typically utilize part of the UHF band and offer a potentially good solution for streaming real-time popular contents. As both mobile and broadcast industries aim at allowing the transmission of mass multimedia services to mobile devices in a cost-efficient manner, there is a need to analyze feasible options of convergence between both industries to ensure the success of the mobile broadcasting deployments in the future. Then, both industries would benefit from this convergence by exploiting synergies and enabling an optimum use of spectrum.

1.4 Objectives and Thesis scope

This dissertation aims at investigating the use of broadcasting technologies for the provision of mobile multimedia services in 4G mobile broadband networks and the opportunities of mobile broadcasting beyond 4G. This main goal can be divided into several partial objectives listed below:

- To develop a complete simulation platform for LTE eMBMS, including link-level simulator, system-level simulator, link abstraction model and application-level simulator.
- To assess the performance of the provision of mass multimedia services through eMBMS transmissions in both LTE and LTE-A standards, including:
  - Evaluation of the benefits of all eMBMS features defined in the standards.
  - Enhancement of MIMO schemes in MBSFN networks.
  - Optimum delivery of streaming and file download services in eMBMS.
- To analyze the use of eMBMS for vehicular safety communications.
- To analyze feasible options of convergence between mobile and broadcast industry to ensure the success of the mobile broadcasting deployments in the future.

1.5 Research methodology

The performance of any modern communication system must be assessed before proceeding with its physical implementation. Given the enormous complexity of current and future wireless systems like LTE, it is impossible to fully evaluate their performance using only analytical methods. For this reason, system modeling and computer simulation represent a good alternative for the assessment of these systems, achieving a good trade-off between complexity, cost, time of development and accuracy [63].

One possible approach to the cellular network simulation would be a global network modeling, which could reproduce the interaction between a high number of eNBs and UEs. This modeling should take into account traffic aspects and user mobility, and, in addition, consider in detail aspects related to coding, modulation and propagation associated to each one of the eNB-UE links. Nevertheless, a direct simulation of this type would entail a forbidding computational cost. Therefore, the simulation is usually divided into two stages or levels of abstraction in order to reduce such complexity. These levels are known as link-level and system-level simulations, which are linked using link abstraction models as shown in Figure 1.2.

On the one hand, link-level simulations are used to assess the performance of the physical layer and those Medium Access Control (MAC) aspects directly related to the radio interface, such as the HARQ mechanisms. At the link

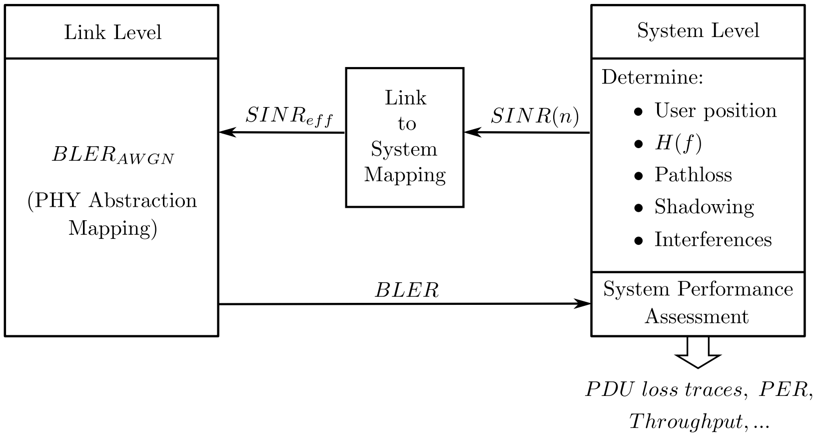

Figure 1.2: Simulation environment used in this dissertation.

level a continuous eNB-UE radio link is modeled, including simulation-specific features like coding, modulation, channel characterization, channel estimation, demodulation, etc. The main results that these simulations provide are the functions which relate BLER with SINR.

On the other hand, a system-level simulator is designed and implemented to allow evaluating the performance of the global network. At this level, system modeling encompasses a set of base stations and all their associated user terminals. The signal level received by each user, as well as other users' interferences and noise, is modeled taking into account the propagation losses and channel fading effects. Then, SINR is calculated for each active user taking into account the current configuration of the network. These SINR values can be then translated to BLER or effective throughput values using the results obtained in the link-level simulations. This way, some measures like Quality of Service (QoS) provided to user and system capacity can be obtained.

As Figure 1.2 shows, although both simulation levels are independently implemented and assessed, the results obtained in link-level simulations act as an interface between both levels. This interaction between link and system-level simulators is usually referred to as Link-to-System (L2S) mapping or link abstraction models.

1.6 Outline of the Thesis and main contributions

The dissertation is organized into six main chapters and one appendix as follows:

Chapter 2 describes the eMBMS system and presents illustrative performance evaluation results with eMBMS system simulations. It also presents simulation results quantifying the gain in the broadcast service data rate that can be achieved using MIMO techniques. Chapter 3 investigates the optimum delivery of both streaming and file download services in eMBMS focusing on the trade-off between PHY-FEC and AL-FEC. Chapter 4 investigates the use of broadcasting for the delivery of road safety services and compares with unicast delivery by means of system-level simulations and a cost modeling analysis. It also addresses open issues to support this kind of applications over the current eMBMS architecture. Chapter 5 deals with the evolution of mobile broadcasting towards Fifth Generation (5G). It analyzes the potential benefits of a convergence between mobile broadband and broadcast industries. In Chapter 6 conclusions to the entire dissertation are drawn. Suggestions on future research topics are also provided.

Appendix A provides a description of the eMBMS performance evaluation methodology using dynamic simulations. It describes the link-level simulator, the system-level simulator and the link abstraction models used during this dissertation to obtain all performance results.

The key contributions of the dissertation in each chapter are summarized next, including references to the most relevant dissertation publications of the author. The complete list of publications can be found in the next section.

Chapter 2 - eMBMS system description and performance evaluation

Although the first part of this chapter presents no original contribution, it describes all eMBMS features introduced from the first release of LTE –Release 8– to the last release of LTE-A –Release 12–. The eMBMS features presented in this chapter are related to all layers, from the physical layer to the application layer.

After describing the eMBMS system, it analyses the benefits of the eMBMS physical layer aspects regarding MBSFN deployments [64]. The eMBMS performance evaluation focuses on the effect of the MBSFN area size on the coverage level and the eMBMS service data rate.

This chapter also identifies the current limitations of the eMBMS physical layer aspects by comparing with the broadcast technology of the IEEE 802.16m standard, known as Enhanced Multicast and Broadcast Services (E-MBS) [65]. In particular, the performance of eMBMS can be improved by using dedicated carriers and MIMO techniques. The performance of spatial multiplexing in mobile broadcast transmissions is investigated in this chapter.

Chapter 3 - Optimum delivery of eMBMS services

The main contribution of this chapter is the analysis of the optimum delivery of streaming and file download services in eMBMS focusing on the Radio Resource Management (RRM) problem and the trade-off between PHY-FEC and AL-FEC.

Concerning streaming services, this chapter performs different studies to evaluate the benefits of AL-FEC in different MBSFN networks [66]. The studies use different combinations of MCSs, AL-FEC code rates and protection periods to assess the effect on coverage level and streaming service data rate. The assessments are based on several quality criteria in order to represent the QoS of a streaming service perceived by users. Moreover, this chapter investigates how the conditions of the scenario in terms of SINR affect the selection of PHY-FEC and AL-FEC parameters. It also investigates the different alternatives of eMBMS scheduling to determine how different services must be multiplexed within the AL-FEC interleaving time.

Concerning file delivery services, this chapter analyses the duration of the transmission required to guarantee the correct file reception, which depends on the number of resources allocated to eMBMS and the transmission data rate. As the inclusion of eMBMS in the same carrier has an impact on the performance of unicast users, this chapter investigates how this degradation can affect to the system throughput [64]. In addition, as the file delivery over eMBMS cannot guarantee that all users properly receive the file, a post-delivery repair phase can be performed to complete the download. The repair phase employs by default p-t-p transmissions, but also p-t-m transmission can be used in case too many users fail to receive the file. This chapter describes this hybrid approach assessing its performance.

Chapter 4 - Use of eMBMS for vehicular safety applications

This dissertation also addresses new use cases and applications for mobile broadcasting beyond typical streaming and file download services. In this chapter we discuss the different alternatives for carrying road safety applications using LTE networks. Although the use of LTE cellular networks for the delivery of ITS applications such as CA and RHW applications has been already considered in the literature, this chapter studies the use of eMBMS for the delivery of these services.

The main contribution of this chapter is the evaluation of the benefits (in terms of resource usage and cost delivery savings) that can be achieved using eMBMS for the delivery of ITS applications [67]. The chapter also addresses the open issues to support road safety applications over current eMBMS architecture, the configuration of the ITS server in charge of distributing safety messages as well as on its interaction with the mobile network operator. In particular, an important contribution of this chapter is the merge of both Broadcast Multicast - Service Center (BM-SC) and ITS server in a single node. The work performed by the author in this topic lead to two patent applications that are currently under review. The former focuses on the distribution of RHWs in dynamic broadcasting areas. The invention is based on the dynamic selection of the MBSFN area that better matches the relevant area of each RHW. The latter proposes an efficient method for the delivery of CA, based on a smart filtering at the ITS server, and a new communication channel from the base stations to the ITS server in order to optimize the delivery.

Chapter 5 - Evolution of mobile broadcasting towards 5G

This dissertation addresses cooperation solutions between mobile and broadcast industries. This chapter reviews the state of the art on mobile and broadcast technologies and the current trends for convergence between both industries. Although the integration of both networks is on the roadmap of mobile and broadcast industries, there are still some challenges that this chapter identifies.

The investigation of first approaches focuses on the cooperation between 3GPP and DVB systems mainly based on the FEF of DVB-T2 standard, which allows combining in the same frequency broadcast and cellular transmissions via time multiplexing, and the carrier aggregation feature of LTE-A, which allows temporarily using a broadcast frequency for cellular transmissions [68].

These approaches for the cooperation between both industries are the starting point for the research on the requirements and functionalities that the future 5G mobile networks must address in order to make an efficient and flexible cellular-broadcasting convergence [69], where both industries would benefit by exploiting synergies and enabling an optimum use of spectrum based on coordinated spectrum sharing.

1.7 List of publications

International journals

[IJ1] J. F. Monserrat, **J. Calabuig**, A. Fernández-Aguilella, and D. Gómez-Barquero, "Joint Delivery of Unicast and E-MBMS Services in LTE Networks," *IEEE Transactions on Broadcasting*, vol. 58, no. 2, pp. 157-167, June 2012.

[IJ2] **J. Calabuig**, J. F. Monserrat, D. Martín-Sacristán, and J. Olmos, "Comparison of Multicast/Broadcast Services in LTE-A and IEEE 802.16m Networks," *Wireless Communications and Mobile Computing*, vol. 14, no. 7, pp. 717-728, May 2014, (first published online in March 2012).

[IJ3] **J. Calabuig**, J. F. Monserrat, D. Gozálvez, and D. Gómez-Barquero, "AL-FEC for Streaming Services in LTE E-MBMS," *EURASIP Journal on Wireless Communications and Networking*, vol. 2013, no. 73, March 2013.

[IJ4] **J. Calabuig**, J. F. Monserrat, D. Gómez-Barquero, and N. Cardona, "Cooperative Spectrum Sharing of Cellular LTE-Advanced and Broadcast DVB-T2 Systems," *Transaction on IoT and Cloud Computing*, vol. 1, no. 1, pp. 1-16, December 2013.

[IJ5] **J. Calabuig**, J. F. Monserrat, D. Gozálvez, and O. Klemp, "Safety on the Roads: LTE Alternatives for Sending ITS Messages," *IEEE Vehicular Technology Magazine*, vol. 9, no. 4, pp. 61-70, December 2014.

[IJ6] **J. Calabuig**, J. F. Monserrat, and D. Gómez-Barquero, "5th Generation Mobile Networks, a New Opportunity for the Convergence of Mobile Broadband and Broadcast Services," *IEEE Communications Magazine*, vol. 53, no. 2, pp. 198-205, February 2015.

International conferences

[IC1] D. Gómez-Barquero, J. F. Monserrat, A. Fernández, **J. Calabuig**, and N. Cardona, "Efficient Multicast and Broadcast Services in Long Term Evolution," in *COST2100 Pervasive Mobile & Ambient Wireless Communications*, Technical University of Vienna, Ed., September 2009, pp. 1-9.

Patents under review

[P1] D. Gozálvez, **J. Calabuig**, and J. F. Monserrat, *Distribution of Road Hazard Warnings in Dynamic Broadcasting Areas.*

[P2] D. Gozálvez, O. Klemp, **J. Calabuig**, J. F. Monserrat, D. Calabuig, and J. J. Gimémez, *Method and device for service following between digital audio broadcasting (DAB) services and enhanced multimedia broadcast/multicast services (eMBMS).*

[P3] D. Gozálvez, O. Klemp, **J. Calabuig**, J. F. Monserrat, D. Calabuig, and D. Martín-Sacristán, *Efficient distribution of Cooperative Intelligent Transport Systems (C-ITS) messages in cellular networks.*

Chapter 2

eMBMS system description and performance evaluation

The 3GPP issued the first version of eMBMS in Release 9. That version includes the physical layer aspects related to eMBMS already defined in Release 8 and the upper layer specifications for its implementation. This chapter describes the eMBMS system and presents illustrative performance evaluation results with eMBMS system simulations. Firstly, Section 2.1 describes the most important aspects of the eMBMS technology included in the LTE Release 9, from the physical layer to the application layer. In particular, we describe the eMBMS network elements introduced in the LTE logical architecture, the higher layer aspects of eMBMS services and use cases, the eMBMS-related channels within the LTE radio protocol architecture, the eMBMS physical layer configuration and the scheduling of eMBMS data within LTE system. In addition, this section summarizes the different eMBMS improvements that have been included in later releases. In Section 2.2, we present some eMBMS performance evaluation results regarding MBSFN deployments. Finally, Section 2.3 summarizes the main conclusions of this chapter.

2.1 System description

2.1.1 Network architecture

In contrast to the Circuit-Switched (CS) model of previous cellular systems, LTE has been designed to support only Packet-Switched (PS) services. It aims at providing seamless IP connectivity between UE and the Packet Data Network (PDN), without any interruption in the end users' applications during mobility. LTE comprises the evolution of the radio access through the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and it is accompanied by an evolution of the non-radio aspects, known as System Architecture Evolution (SAE), that includes the Evolved Packet Core (EPC) network. LTE jointly with SAE comprise the Evolved Packet System (EPS) [70].

On the one hand, the E-UTRAN consists of eNBs, which provide the user plane and control plane protocol terminations towards the UE. The protocols which run between eNB and UEs are known as the Access Stratum (AS) protocols. On the other hand, the EPC is responsible for the overall control of the UE and the establishment of the bearers, where the main logical nodes are the PDN Gateway (P-GW), the Serving Gateway (S-GW) and the Mobility Management Entity (MME). The P-GW is the interconnect point between the EPC and the external IP networks. It also performs several functions such as IP address allocation for the UE or policy control and charging. The S-GW is the point of interconnect between the E-UTRAN and the EPC. It serves the UE by routing the incoming and outgoing IP packets. The MME handles the signalling related to mobility and security for E-UTRAN access. The protocols running between the UE and the Core Network (CN) are known as the Non-Access Stratum (NAS) protocols.

- Network elements related to eMBMS

In Release 9, the 3GPP introduced new elements into the EPS network architecture to support eMBMS [5, 71]. Figure 2.1 shows the overall network architecture including the new network elements related to eMBMS. They are the Broadcast Multicast - Service Center (BM-SC), the Multimedia Broadcast Multicast Services Gateway (MBMS GW) and the Multicell Coordination Entity (MCE).

- BM-SC: already defined in Release 6, the BM-SC is the interface between external content providers, like mobile video service providers, and the CN. The main functions provided by the BM-SC are the reception of MBMS content from external content providers, to providing application and media servers for the MNO, MBMS services announcement and scheduling, and delivery of MBMS content into the core network.

- MBMS GW: the main function of the MBMS GW is to forward the MBMS packets to the eNBs involved in the eMBMS transmission using IP multicast. The MBMS GW performs MBMS Session Control Signaling through the MME to set up MBMS radio bearers in the E-UTRAN.

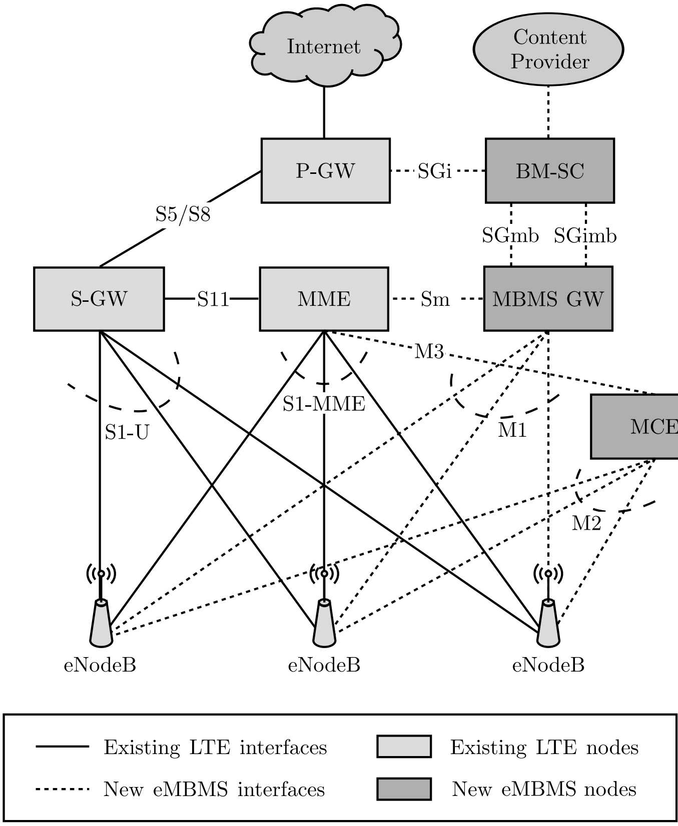

Figure 2.1: LTE logical architecture with eMBMS network elements.

- MCE: the management of both MBMS content and resources is performed by the MCE. It is a control entity responsible for the admission control and the resource allocation. In case of MBSFN operation, the MCE jointly manages the radio resources of all the eNBs in the MBSFN area. The MCE can even decide not to establish a new MBMS radio bearer if the available resources do not allow the incoming service. In addition to allocate the radio resources, the MCE must decide on the MCS that guarantees the coverage requirements. Finally, the MCE is involved in the MBMS Session Control Signaling, but it does not perform UE-MCE signaling.

The 3GPP specifications define two different ways of integrating the MCE in the network [5]. One option is to locate the MCE directly into the LTE base station, which would be very cost-effective, as it is in most cases only a software upgrade to existing hardware. However, the drawback of this option is that only cells that belong to that particular eNB can form that MBSFN area. To avoid this limitation, the MCE can be added as a separate network element and then, of course, can serve different eNBs. This last option is the one shown in Figure 2.1.

Figure 2.1 also shows the new interfaces defined to support MBMS in LTE networks. They consist of two new control plane interfaces (M3 and M2) and one new user plane interface (M1).

- M3 Interface [72]: it is the interface between the MME and MCE and is involved in procedures like starting, stopping and updating MBMS sessions. The M3 is the reference point for the control plane between MME and E-UTRAN.

- M2 Interface [73]: it is the interface between the MCE and eNB and also is involved in procedures like starting, stopping and updating MBMS sessions. The MCE provides through M2 the details of the radio resource configuration that all participating eNBs shall apply. In particular, the MCE provides the updated control information to be broadcast by the eNBs.

- M1 Interface [74]: it is the reference point between MBMS GW and E-UTRAN for MBMS data delivery. The GTP-U4 protocol over User Datagram Protocol (UDP)/IP is used to transport MBMS data streams over the M1 interface and IP multicast is used for p-t-m delivery to the eNBs involved in the transmission of an MBMS service.

2.1.2 eMBMS services and use cases

- MBMS functional layers

Three distinct functional layers are defined for the delivery of a service based on MBMS. They are bearers, delivery methods and user services:

- MBMS bearers: they provide the mechanism by which IP data are transported. MBMS bearers are used to transport multicast and broadcast traffic in an efficient p-t-m manner and are the foundation of MBMS-based services. Besides, MBMS bearers may be used jointly with unicast in offering complete service capabilities.

- MBMS delivery methods: one or more delivery methods are used when delivering MBMS content to a receiving application. This layer provides functionality such as security and key distribution, reliability control by means of FEC mechanisms and associated delivery procedures such as file-repair, delivery verification. Download and streaming delivery are the two delivery methods defined. These delivery methods may use MBMS bearers and may make use of p-t-p bearers through a set of MBMS associated procedures.

- MBMS user services: they can built on top of the MBMS bearer service and enable applications. Different applications impose different requirements when delivering content to MBMS subscribers and may use different MBMS delivery methods.

- MBMS user service entities and relations

An MBMS user service is an entity that is used in presenting a complete service offering to the end-user and allowing him to activate or deactivate the service. It is typically associated with short descriptive material presented to the end-user, which would potentially be used by the user to decide whether and when to activate the offered service.

A single service entity can contain multiple distinct multimedia objects or streams, which may need to be provided over various MBMS download or MBMS streaming sessions. A download session or a streaming session is associated with either an unicast bearer or one or more MBMS bearers and a set of delivery method parameters specifying how content is to be received on the mobile side. The MBMS user service session may be mapped either on MBMS bearer services or on unicast bearer services.

A set of one or more MBMS bearers can be used for delivering data as part of an MBMS download or streaming session. As an example, the audio and visual parts can be carried on separate MBMS bearers. However, it is recommended to transfer on the same MBMS bearer service MBMS download and/or streaming sessions which belong to the same MBMS user service.

Moreover, an MBMS bearer service, which is identified by Temporary Mobile Group Identity (TMGI), may be used to transport data for one or more MBMS download or streaming sessions. The BM-SC allocates a globally unique TMGI per MBMS bearer service, which can be obtained via service announcement.

- MBMS user service procedures

Four main procedures are defined for the provision of an MBMS user service. They are the following [13]:

- User service discovery/announcement: it provides all necessary information about available services and needed parameters to become member of a service. This procedure can provide information on available MBMS user services in pull mode, via the Web or WAP portals, or in push mode, via SMS or MBMS download delivery.

- User service initiation/termination: for MBMS user service activation, the UE needs to perform a security function and the MBMS bearer service activation procedures. In case the service requires user authentication, security procedures are performed before the MBMS bearer service activation procedure

- Session start/stop: the BM-SC controls the activation and the release of the MBMS user plane. The service provider might trigger this proces on the availability of new content. The release of the user plane resources depends on the transmission duration of the content.

- Data transmission: on the one hand, the "MBMS user service transmitter" contains the MBMS user service specific transmission protocols shown in Figure 2.2. Optionally, the content is protected by a FEC code. The traffic is sent using either IP unicast addressing or IP multicast. On the other hand, the "MBMS user service receiver" combines the reception via the MBMS bearer service and interactive bearer services in a controlled way.

Additionally, some associate-delivery procedures can be used in the reception of MBMS user services. In particular, it is possible for UEs to repair erroneous files, delivered by the download delivery method, by means of repair

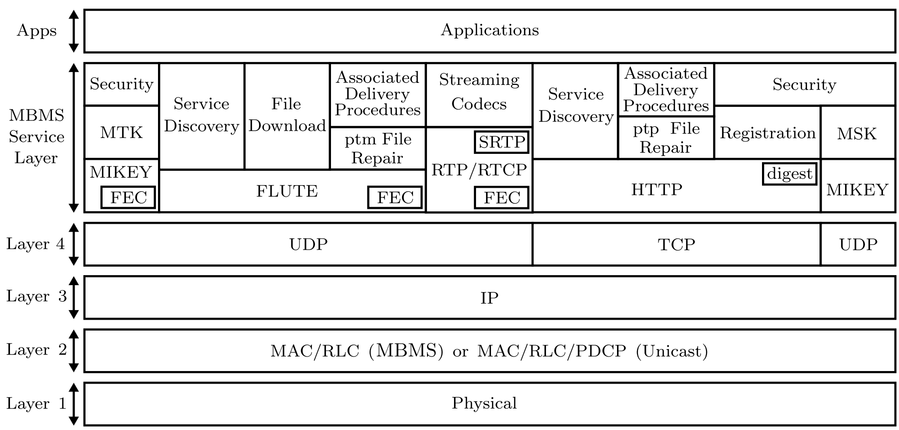

Figure 2.2: eMBMS protocol stack.

request and response operations. In addition, it is also possible for the operator to collect statistical data such as lost frames, assigned resources and bit-rates achieved, among others.

- Delivery methods and use cases

As mentioned before, two different delivery methods are defined in eMBMS. On the one hand, the MBMS download delivery method allows the error-free transmission of files via the unidirectional MBMS bearer services. The files are downloaded and stored in the local files-system of the UE. The network triggers the transmission since the users are registered to the download service. Files may contain multimedia components or any other binary data. In addition, the MBMS download delivery method allows the transmission of an arbitrary number of files within a single data transfer phase. On the other hand, the MBMS streaming delivery method aims at continuous transmission of data and the immediate play-out via the display and/or the loudspeaker. Mobile terminals retrieve transmission details like multicast IP address, TMGI and the used ports before the MBMS UEs can activate the reception. Upon interaction of the user and when all parameters are known, the UE tunes in the transmission and stays until the user decides to leave the transmission. This can happen before the transmission ends.

Table 2.1 summarizes different use cases for eMBMS user services and the delivery method associated to each use case [6].

2.1.3 Radio protocol architecture

Figure 2.3 illustrates the overall radio protocol architecture of E-UTRAN, which is divided into control plane and user plane [70]. It also shows the use of radio bearers, logical channels, transport channels and physical channels.

- Control plane

The control plane is referred as the AS control plane, which handles radio-specific functionalities, and the NAS control plane, which is referred to as the higher layers and handles functions like Public Land Mobile Network (PLMN) selection, tracking area update, authentication, and EPS bearer establishment, modification and release.

The Radio Resource Control (RRC) is part of the radio interface control plane and supports the transfer of common NAS information and dedicated NAS information. The former is applicable to all UEs whereas the latter is applicable only to a specific UE. The main functions of this control protocol are the provision of system information, the notification of incoming calls via

Table 2.1: Use cases for eMBMS.

Use case	**Description**	**Delivery method**
Live event streaming	Venue casting (stadiums/arenas), or local, or nationwide	Streaming
Mobile TV	Mainstream or other TV channels, new interactive services	Streaming
Video on demand	Multiple users downloading the most popular content	Download
News feeds	News, weather, stock market prices, commodity prices	Download
Radio station streaming	High quality digital radio	Streaming
Media delivery	e-Newspaper, music tracks, video services, apps updates, firmware updates	Download
Advertising	Localised or event specific, e.g., stadiums, malls, digital billboards	Download
Connected vehicles	In-vehicle display e.g., hires navigation maps, on-board systems updates, in-car entertainment	Streaming and download
Location based services	Hotels, concourses, train stations, bus stops	Streaming and download
Public safety	Instructions, news updates	Download
Internet of things	Scalable to support growth of connected objects	Download

paging, the management of the RRC connection, mobility functions, and the measurement configuration and reporting.

- User plane

The E-UTRAN user plane protocol stack consists of three sublayers belonging to the LTE Layer 2. They are the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC). In the control

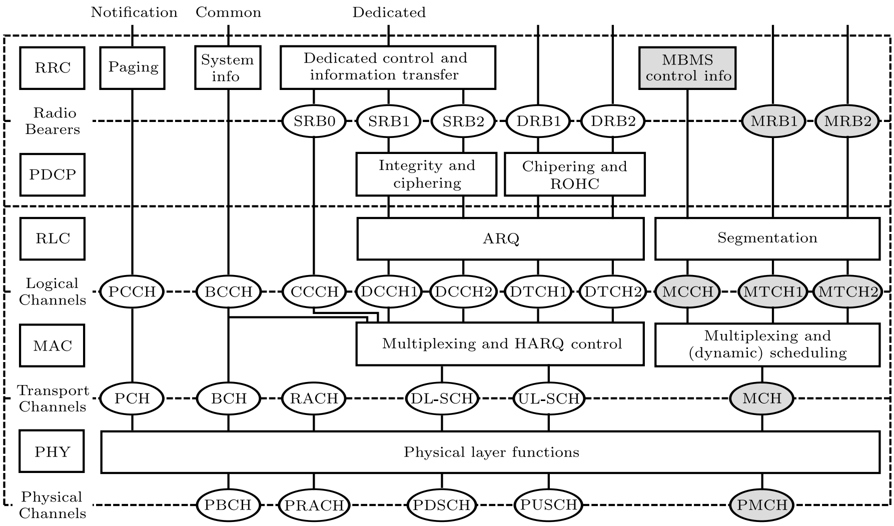

Figure 2.3: LTE radio protocol architecture.

plane, the PDCP layer processes RRC messages whereas it processes IP packets in the user plane. The main functions of the PDCP layer are header compression, integrity and ciphering. Regarding the RLC layer, its main functions are segmentation and reassembly of upper layer packets, and Automatic Repeat request (ARQ). The MAC layer performs multiplexing of data from different radio bearers and HARQ.

In addition, the MAC layer performs the mapping between logical channels and transport channels. Each logical channel type is defined depending on the type of information that it transfers. In general, the logical channels can be classified in two groups, the control channels and the traffic channels. The formers are the Broadcast Control Channel (BCCH), used for broadcasting system control information; the Paging Control Channel (PCCH), to transfer paging information and system information change notifications; the Common Control Channel (CCCH), used to transmit control information between UEs and network; and Dedicated Control Channel (DCCH), for transmitting dedicated control information between a UE and the network. On the other hand, the channel for unicast data traffic is the Dedicated Traffic Channel (DTCH), which transfers the user information.

The data from the MAC layer is exchanged with the physical layer through transport channels. The downlink transport channels are the Broadcast Channel (BCH), which transports part of the system information; the Downlink Shared Channel (DL-SCH), used to transport downlink user data or control messages and the remaining parts of the system information; and the Paging Channel (PCH), which transports paging information to UEs and informs them about updates of the System Information (SI). The uplink transport channels are the Uplink Shared Channel (UL-SCH), which is used to transport uplink user data or control messages; and the Random Access Channel (RACH), used to access to the network.

- eMBMS-related channels

In order to support eMBMS, the radio protocols and the structure of channels are extended in Release 9, including two logical channels, the Multicast Traffic Channel (MTCH) and the Multicast Control Channel (MCCH); one transport channel, the Multicast transport Channel (MCH); and one physical channel, the Physical Multicast Channel (PMCH).

The MTCH is a p-t-m downlink channel for transmitting data traffic from the network to the UE. It carries data corresponding to a certain multimedia content, either a streaming service or a file delivery service. In LTE, the MBMS control information of one or several MTCHs are provided by the MCCH, which also is a p-t-m downlink channel. There is always one MCCH per MBSFN area, i.e. an MCCH carries control information related to all MBMS services provided in that MBSFN area. Some of the control information that MCCH includes are the subframe allocation and the MCSs used to transmit MBMS services over LTE.

Both MTCH and MCCH channels can be mapped into the MCH. This transport channel carries one single MCCH channel and from one to several MTCH channels. Finally, the MCH transport channel is mapped into the PMCH, which has different characteristics as compared with the Physical Downlink Shared Channel (PDSCH) used for unicast transmissions. The physical layer configuration is described in the next section. As eMBMS is used in downlink transmission, the description is focused in the physical layer for downlink.

2.1.4 Physical layer configuration

- Time-frequency resources

The LTE downlink transmission from the eNB consists of user plane and control plane data, which derives from the higher layers in the protocol stack, multiplexed with physical layer signalling to support the data transmission. This multiplexing is performed by using OFDMA, which enables the downlink signal to be subdivided into small units of time and frequency.

More concretely, the LTE downlink resources have dimensions of time, frequency and space. Concerning the spatial dimension, it is accessed by means of multiple "antenna ports" at the eNB. For each antenna port, a Reference Signal (RS) is provided to enable the UE to estimate the radio channel. In time, the transmission in downlink and uplink is organized into radio frames of a duration of 10 ms. 3GPP defines two different radio frame structures, one applicable to FDD and one applicable for TDD. Each 10 ms radio frame is divided into ten subframes of 1 ms, which consist of two slots of 0.5 ms. Each slot comprises a number of OFDM symbols which depends on the used CP type. Regarding the frequency domain, resources are grouped in units of several contiguous subcarriers, which depends on the OFDM subcarrier spacing, that occupy a total of 180 kHz. Thus, a Resource Block (RB) is composed by one slot of 0.5 ms and 180 kHz, although the smallest unit of resource is the Resource Element (RE), which consists of one subcarrier for a duration of one OFDM symbol [9].

Table 2.2 shows the possible configurations of both CP and OFDM subcarrier spacing. For unicast transmissions, the transmission scheme in downlink is based on conventional OFDM with a subcarrier spacing of 15 kHz. For that case, there are two CP lengths, normal –4.6 μs– and extended –16.7 μs–, corresponding to seven and six OFDM symbols per slot, respectively. Although both normal and extended CP can be used for unicast transmissions, the use of the normal CP is more usual for unicast. Then, the extended CP is defined mainly for eMBMS transmissions as it allows larger MBSFN area sizes by avoiding ISI. The use of the extended CP allows the construction of SFNs between multiple cells with a maximum of 5 km ISD. In addition, an optional extended CP length of around 33 μs can be used for eMBMS in scenarios with large ISDs (10 km SFN distance). For this CP, 3GPP defines a subcarrier spacing of 7.5 kHz. However, the double CP length feature is only available in MBSFN dedicated carrier deployments, which is not supported in current releases of LTE and LTE-A.

- Physical channels and signals

Within a RB, a RE can be used to map physical channels or physical signals. A physical channel corresponds to a set of REs carrying information which is originated from higher layers whereas a physical signal corresponds to a set of REs carrying a signal originated at the physical layer.

On the one hand, the different downlink physical channels are the Physical Downlink Shared Channel (PDSCH), which is used basically for user data transport; the Physical Broadcast Channel (PBCH), which provides critical system information; Physical Multicast Channel (PMCH), which carries

Table 2.2: Physical resource blocks parameters.

Configuration		CP length	Number of OFDM symbols	Number of subcarriers
CP type	Subcarrier spacing			
Normal	15 kHz	4.6 μs	7	12
Extended	15 kHz	16.7 μs	6	12
Extended	7.5 kHz	33.3 μs	3	24

data for MBMS; the Physical Control Format Indicator Channel (PCFICH), which indicates the number of OFDM symbols used for transmission of control channel information in each subframe; the Physical Downlink Control Channel (PDCCH), which conveys UE-specific control information; and the Physical Hybrid ARQ Indicator Channel (PHICH), which carries the HARQ ACK/NACK from eNB. It is worth noting that the PMCH can only be transmitted in certain specific subframes known as MBSFN subframes, which are indicated in the system information carried on the PDSCH.

On the other hand, there are two different types of physical signals in downlink, the synchronization signals and the Reference Signals (RSs). The former are used for synchronization issues, initial acquisition and handover, whereas RSs are used mainly for channel estimation. In LTE downlink, there are five different types of RS [70]: the cell-specific or common RSs, the UE-specific RSs, the MBSFN RSs, the positioning RSs and the Channel State Information (CSI) RSs.

The cell-specific RSs enable the UE to determine the phase reference for demodulating the downlink control channels and the downlink data in most transmission modes of the PDSCH. Up to four cell-specific antenna ports, numbered 0 to 3, may be used by an LTE eNB and, for each antenna port, a different RS pattern has been designed. The MBSFN RSs are used only for MBSFN operation within the subframes allocated to eMBMS and they are mapped on the antenna port 4. Figure 2.4 shows the cell-specific RS patterns for normal and extended CP, and the MBSFN RS patterns for a subcarrier spacing of 15 and 7.5 kHz. In order to simplify the figure, only the pattern of one antenna port is shown for cell-specific RS. As it can be seen, the assigned resource elements for the MBSFN operation are closer in the frequency domain as compared with the cell-specific RS pattern. This is because the use of MBSFN implies longer delay spreads and, consequently, a reduction in the coherence bandwidth.

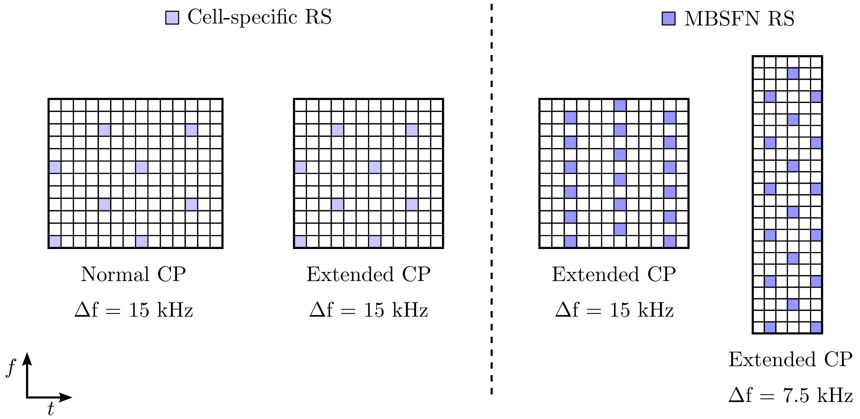

Figure 2.4: Cell-specific and MBSFN reference signal patterns.

2.1.5 eMBMS scheduling

The scheduling of MBMS services in LTE is not performed in the PDCCH as unicast services. Within an MBSFN subframe, the MCH uses all the resources in the frequency domain, so MCH-related scheduling only relates to the subframe allocation in the time domain.

Some of the eMBMS scheduling information is provided by System Information Blocks (SIBs) transmitted through BCCH. There are two SIBs related to eMBMS in LTE: SIB2 and SIB13. The former only informs the user about which subframes are reserved for MBSFN in downlink. However, this information is not enough to receive an MBMS service. With this aim, the SIB13 informs about the different MBSFN areas configured in a cell. It indicates the subframes that carry the MCCH of each area and the MCS –signaling MCS– used for its transmission.

It is important to note that resources are allocated to MBSFN in units of subframes. Besides, among the 10 subframes included in a radio frame, only subframes #1, #2, #3, #6, #7 and #8 can be allocated to MBSFN. Subframes #0 and #5 are reserved for synchronization signals, whereas subframes #4 and #9 are reserved for paging, and they are also necessary to ensure that there are enough reference signals to decode the SIBs. MCCHs are found in one of the MBSFN-capable subframes, periodically, with the period informed in the SIB13.

The information provided by the SIB13 allows the user to read the MCCH of each area. A MCCH contains the message known as *MBSFNAreaConfiguration*, which indicates the subframes where the different MTCHs configured in the associated MBSFN area are transmitted. This message carries several information elements such as the Common Subframe Allocation (CSA) pattern, the CSA period, and the PMCH-InfoList. The first two elements are used to indicate which subframes are reserved for all the MCHs of an MBSFN area, whereas the latter indicates how the subframes are shared among those MCHs. More precisely, PMCH-InfoList indicates the last subframe allocated to each MCH through MCH Subframe Allocation (MSA) end. In addition, PMCH-InfoList reports the MCS of each MCH.

Each MCH can multiplex several MBMS services. In order to identify the specific MBMS service, the PMCH-InfoList defines all the MBMS ongoing sessions (identified by MTCH). The scheduling of which subframes are used for a particular MTCH is performed once per MCH Scheduling Period (MSP). In particular, this scheduling is informed in the first subframe of that period, where a MAC control element named MCH Scheduling Information (MSI) specifies how the different sessions are multiplexed during the MSP. For that, it indicates the subframe where each MTCH ends in this MSP.

In order to clarify the MBMS scheduling in LTE, Figure 2.5 shows an example of MBMS scheduling configuration. Four subframes are assigned to MBMS: #1, #2, #6, and #7. The repetition period of the MCCH is 320 ms. The CSA period where two different MCH are scheduled is 160 ms. Each MCH has two MBMS services: MTCH 1 and MTCH 2 correspond to MCH 1 while MTCH 3 and MTCH 4 correspond to MCH 2. The MSPs are 160 and 320 ms for MCH 1 and MCH 2, respectively. Note that SFN in Figure 2.5 means system frame number.

2.1.6 eMBMS standard evolution

The work on eMBMS has continued within 3GPP since the first version of the eMBMS technology in Release 9. Table 2.3 summarizes the eMBMS enhancements introduced in the LTE-A releases –Release 10, 11 and 12.

The most important features of Release 10 are the definition of a counting mechanism and the support of Progressive Download and Dynamic Adaptive Streaming over HTTP (3GP-DASH). On the one hand, the counting procedure enables E-UTRAN to determine how many UEs are receiving, or are interested in receiving, an MBMS service via an MBSFN Radio Bearer (MRB) (i.e., using the MBSFN mode of operation). Based on the counting results, E-UTRAN may decide to start or stop MBSFN transmission of a given MBMS service [8]. On the other hand, 3GP-DASH enables to provide services to deliver continuous media content over Hypertext Transfer Protocol (HTTP) in a sense that all resources that compose the service are accessible through HTTP-URLs. In addition, the HTTP protocol may be used to deliver the metadata and media data composing the service. This enables that standard HTTP servers and

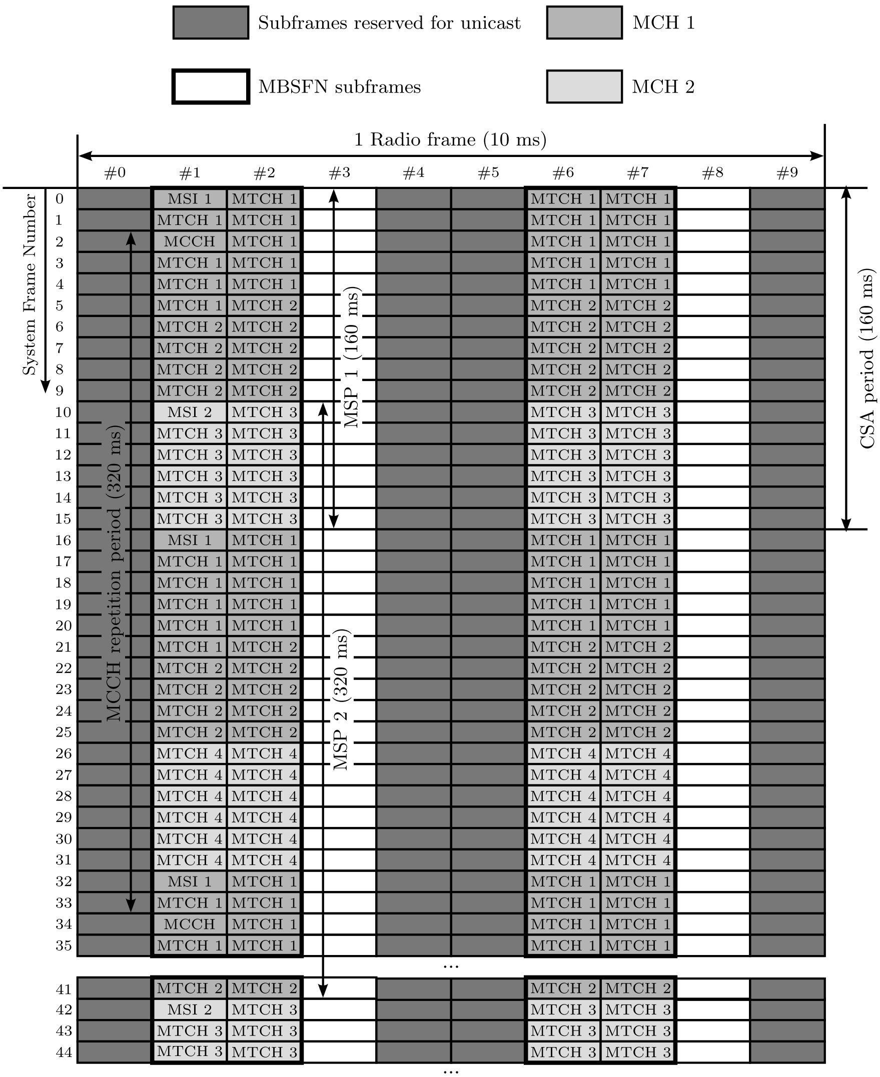

Figure 2.5: MBMS scheduling parameters in LTE.

standard HTTP caches can be used for hosting and distributing continuous media content.

The improvements of eMBMS in Release 11 are the support of service continuity and some enhancements at the service layer [10]. Regarding the service

Table 2.3: eMBMS enhancements introduced in the LTE-A releases.

Enhancement	**Release**
Counting mechanism to enable the network to know the reception status of UEs receiving a given MBMS service in the RRC connected mode	Release 10
Enable statistical multiplexing gains for variable bit rate services	Release 10
Support of Allocation and Retention Priority (ARP) to enable priority between eMBMS sessions	Release 10
Support of unicast reception in MBSFN subframes	Release 10
Support for Dynamic Adaptive Streaming over HTTP (DASH) over MBMS	Release 10
Support of service continuity	Release 11
Service layer enhancements	Release 11
MBMS operation on demand	Release 12
Enhanced MBMS operation	Release 12

continuity, the additional enhancements introduced in Release 11 ensure the continuity of MBMS reception while the UE is moving within an MBSFN area or to help UE find services provided on other frequencies. With this aim, a new SIB is defined, which is used by both eMBMS and non-eMBMS cells to provide MBMS service area identifiers of the current frequencies and of neighbour frequencies. In addition, the UE sends MBMS interest indications to the network. The service layer enhancements are the reception reporting aggregation and reception reporting from specific UEs; the inclusion of content schedule information in the User Service Description (USD) to save UE battery life; the pre-FEC repair Quality of Experience (QoE) metrics report to allow operator to optimize FEC configuration of File Delivery over Unidirectional Transport (FLUTE); the unicast file repair with HTTP byte range request; and the location filtering to allow UE to selectively receive a service.

The features introduced in Release 12 focus on two topics. One of them is related to some eMBMS enhancements aspects including MBMS over the air efficiency, MBMS for datacasting and real-time content, and generic signalling of DASH transport over broadcast, multicast and unicast [75]. The other enhancements are related to MBMS operation on demand, which are described in [76]. For example, it enables a BM-SC to convert a non-MBMS unicast service as an MBMS user service, and to distribute the USD describing such MBMS user service to interested UEs.

2.2 Performance evaluation

This section evaluates the performance of the eMBMS physical layer aspects focusing on MBSFN deployments. Firstly, it identifies several eMBMS physical layer that can be enhanced to improve the performance of broadcast transmissions over MBSFN deployments. For this end, eMBMS technology is compared with another mobile broadcast technology such as E-MBS, the broadcast mode of the IEEE 802.16m standard. Afterthat, the application of these features on MBSFN deployments are assessed.

The performance evaluation results presented in this section have been obtained with the simulation platform described in Appendix A, which contains the system modeling and assumptions used for system-level simulations.

2.2.1 eMBMS physical layer limitations

Currently, although the LTE physical layer specifications already include the MBSFN dedicated carrier option, eMBMS is only supported over the same frequency carrier as unicast services. Per contra, the broadcast mode of WiMAX is supported in both modes, that is, in-band with unicast services (sharing the same carrier) and over a frequency carrier dedicated to broadcast transmissions.

The use of broadcast transmission over a mixed unicast-broadcast carrier is a good solution to reduce the eMBMS deployment costs and also allows MNOs to make a dynamic radio resource allocation to either broadcast or unicast radio channels. However, the support of dedicated carriers to broadcast transmissions, as it is included in IEEE 802.16m standard, could extend the use cases of eMBMS. As an example, the use of a dedicated carrier for broadcast transmissions is more suitable for the provision of services like linear mobile TV. Thus, the results presented in these section have been obtained considering the use of dedicated carriers for broadcast transmissions.

Another feature that can enhance the performance of MBSFN deployments is the use of MIMO. Currently, the transmission of eMBMS data is performed using single antenna transmission. On the contrary, the WiMAX IEEE 802.16m specifications include MIMO schemes for E-MBS. They are based on open-loop Spatial Multiplexing (SM) schemes for enhancing data rate and reliability.

2.2.2 Simulation assumptions

Table 2.4 summarizes the system-level simulation parameters assumed in this section. It was considered the network layout related to the Urban Macrocell (UMa) scenario described in Section A.2.2, which consists of 57 cells constituted by 19 sites, each one with 3 cells. The ISD is 500 m. In these simulations, different MBSFN area sizes were considered and users were uniformly distributed within cells that pertain to the MBSFN area. The serving cell is, by default, the closest one, unless any other was more than 1 dB over its signal level. The cells surrounding the MBSFN area transmit other eMBMS services in the same band and, therefore, act as interferers.

The performance evaluation of MBSFN deployments focuses, firstly, on the effect of the MBSFN area size on the coverage level and the broadcast service data rate. In addition, the use of MIMO in MBSFN deployments was also analyzed in terms of coverage level and broadcast service data rate. Only a finite set of broadcast service data rates was considered. These broadcast service data rates are the data rates provided to the application layer using the set of MCS related to the 15 entries of the Channel Quality Indicator (CQI)

Table 2.4: System-level simulation parameters for the eMBMS performance evaluation.

Parameter	**Value**
Bandwidth	5 and 10 MHz
Central frequency	2 GHz
Transmission power	43 dBm for 5 MHz 46 dBm for 10 MHz
Antenna tilt	12°
Noise spectral density	-174 dBm/Hz
UE noise figure	9 dB
Penetration loss	20 dB
Large-scale channel model parameters	IMT-Advanced UMa
Multipath channel model	ETU PDP, speed = 3 km/h
Interference modeling	Explicit

table of LTE (see Table A.3) and to the 16 entries of the CQI table of IEEE 802.16m [77]. It is worth noting that the broadcast service data rate at the application layer depends not only on the MCS used but also on the IP packet size and all the overheads in the protocol stack. In these simulations, a typical IP packet size of 1500 bytes was assumed.

In the analysis, three main performance indicators were assessed [78]:

- The outage probability: a user is in outage when experiencing a Packet Error Rate (PER) greater than 1%.
- The coverage level: the coverage percentage for a given MCS represents the percentage of cell locations –or equivalently users– that are not in outage for this MCS.
- The maximum MCS supported: it is defined as the highest MCS that ensure a coverage level greater than 95%.
- The maximum broadcast service data rate: this metric is obtained taking into account the maximum MCS supported and all the overheads in the protocol stack.

2.2.3 Effect of MBSFN area size on eMBMS system performance

The main advantage of using MBSFN networks to provide broadcast services is the mean SINR increase and the reduction in the interference level, which results in a better coverage range. In general, the coverage level depends on the MCS, obtaining better coverage for more robust MCS (small MCS) and a lower level of coverage for less robust MCS (high MCS). In MBSFN, the coverage level also depends on the amount of synchronized cells transmitting the same information in the same resource block, i.e. the MBSFN area size. The relationship between the coverage level and the MCS for different MBSFN area sizes is shown in Figure 2.6

It was found out that, obviously, users have a better coverage level when they receive the combined signal from a greater number of cells, especially for high MCS. For example, with an MBSFN area of 7 cells (a center cell plus one ring of cells), the maximum MCS supported is MCS 5, whereas an MCS 6 is achieved if an MBSFN area of 19 cells (center cell plus two rings of cells) is used. Besides, given a fixed MCS and a target coverage level of 95%, the optimal number of cells per MBSFN area was different. With MCS 4 an MBSFN area of 2 cells was enough, whereas when using an MCS 6 an MBSFN area of 16 cells was needed. Thus, there is a certain relation between MBSFN area size and maximum MCS supported that must be maintained.

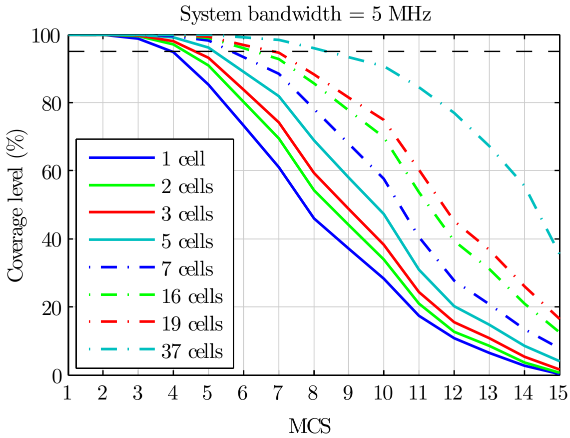

Figure 2.6: Coverage level vs. MCS for different MBSFN area sizes.

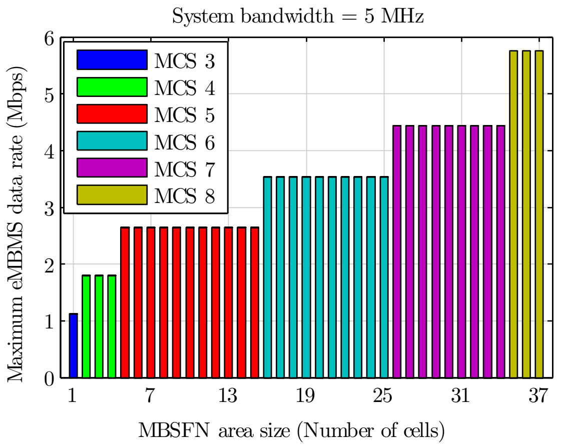

Figure 2.7: Maximum eMBMS data rate vs. MBSFN area size.

Figure 2.7 shows the maximum eMBMS data rate per MBSFN area size. For each MBSFN area size, the MCS was exactly the maximum that ensures the 95% of coverage level. Results show that, logically, the higher the MBSFN area size, the higher the maximum eMBMS data rate and, consequently, a wider range of services per cell. This is because the maximum MCS supported in large MBSFN areas is greater than in small MBSFN areas. Besides, Figure 2.7 illustrates that with 7, 19 and 37 cells in the MBSFN area the maximum eMBMS data rate is 2.64, 3.53 and 5.75 Mbps, respectively. Assuming that, for example, these eMBMS transmissions are used to provide mobile TV services, these eMBMS data rate values correspond to 8, 11 and 19 TV channels of 300 kbps.

2.2.4 Application of MIMO for mobile broadcast transmissions

This section compares the broadcast capabilities of both LTE and IEEE 802.16m technologies focusing on the potential benefits of MIMO schemes in mobile broadcast transmissions.

The relevant system parameters of the broadcast modes of both systems are summarized in Table 2.5. The system parameters of both technologies are based on a 10 MHz system bandwidth. In contrast to LTE, IEEE 802.16m always uses the same subcarrier spacing of 10.94 kHz for all unicast or broadcast transmissions, and there are three possible CPs with durations of 1/16, 1/8, and 1/4 of an OFDM symbol. The last two are specially suited for MBSFN. It is interesting to highlight that WiMAX has more data subcarriers than LTE. Concerning the basic scheduling unit, in LTE the RB is defined as six or seven consecutive OFDM symbols in the time domain –depending on the CP length– and 12 or 24 consecutive subcarriers in the frequency domain –depending on the subcarrier spacing–. On the other hand, the Physical Resource Unit (PRU) in WiMAX comprises five, six or seven consecutive OFDM symbols –depending on the type of subframe– and 18 consecutive subcarriers.

For the performance comparison, LTE was configured with 15 kHz subcarrier spacing and extended CP. The other possible configuration for eMBMS –7.5 kHz with and extended CP of 33.3 μs– was discarded because this is more appropriate for scenarios with large ISDs and frequencies lower than the one used in this study. Regarding WiMAX, two CP length configurations were analyzed –1/4 and 1/8– as the other one is too short to support SFN transmissions. Again, a dedicated carrier was also assumed in which all the resources are allocated to broadcast transmissions without any control channel overhead –neither broadcast nor synchronization channels. For this assessment, different ISD values were assumed. They range between 500 and 2500 m with a step of 500 m.

Figure 2.8 shows the coverage level versus MCS for different ISDs with LTE. As expected, the lower the ISD, the higher the maximum MCS that achieves a coverage level greater than 95%. With larger ISDs, there is higher probability of having users with low SINRs that can only use robust MCS. Note that in this scenario the SINR is practically independent of the interference power. This is not a trivial consideration. Although all cells belong to the same MBSFN, distant cells can become interferers if propagation delays exceed the

Table 2.5: Comparison of LTE and WiMAX system parameters.

Parameter	**3GPP LTE**	**WiMAX IEEE 802.16m**
Bandwidth	10 MHz	10 MHz
Subcarrier spacing (kHz)	15 (unicast and MBSFN) 7.5 (MBSFN only)	10.9375
Data subcarriers	600 (15 kHz) 1200 (7.5 kHz)	864
CP length (μs)	4.6 (normal CP, 15 kHz) 16.7 (extended CP, 15 kHz) 33.3 (extended CP, 7.5 kHz)	5.7 (CP 1/16) 11.5 (CP 1/8) 22.9 (CP 1/4)
Frame structure	One radio frame of 10 ms	One superframe of 20 ms (Four radio frames of 5 ms)
Number of subframes per frame	10 (1 ms)	8 (CP 1/16) 8 (CP 1/8) 7 (CP 1/4)
TX and RX antenna schemes	1x2 (single antenna)	2x2 SM (1 stream or 2 streams)

CP length. Nevertheless, those cells are so distant that signals coming from them are heavily attenuated.

Figure 2.9 compares the maximum broadcast service data rate of LTE and WiMAX systems. With an ISD of 500 m, WiMAX –in all configurations– achieves greater broadcast service data rate than LTE. LTE uses an extended CP of 16.6 μs, which is 1/4 of the OFDM symbol. Therefore, this case is similar to the CP 1/4 used in WiMAX. However, the maximum broadcast service data rate is higher in WiMAX because it can use more data subcarriers than LTE. The maximum broadcast service data rate achieved by LTE is around 33.5 Mbps, whereas in WiMAX –with only one stream– the value is 36.7 Mbps for CP 1/4 and 40.9 Mbps for CP 1/8.

It is worth noting that WiMAX uses more data subcarriers because of the lower subcarrier spacing and the lower number of guard subcarriers. This lower

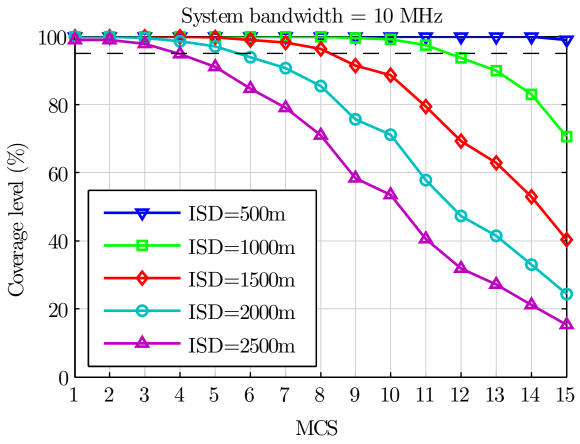

Figure 2.8: Coverage level vs. MCS for different ISDs in LTE.

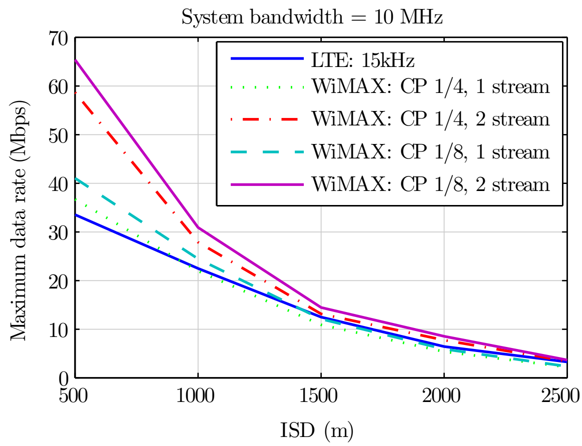

Figure 2.9: Maximum data rate of broadcast modes of LTE and WiMAX for different ISDs.

subcarrier spacing could introduce inter-carrier interference at high velocities, which would decrease the system performance. However, this effect does not appear in our simulations because of the pedestrian user assumption.

However, simulations show that MIMO schemes defined in WiMAX significantly improve its broadcast service performance, outperforming LTE in all cases. MIMO is clearly beneficial with low ISDs given that MIMO behavior is better with higher SINR values. With an ISD of 500 m, the increase in maximum broadcast service data rate obtained with the SM of two streams is around 59%. Nevertheless, the performance gain due to the usage of MIMO decreases as the ISD becomes larger.

2.3 Conclusions

This chapter has described the main features of eMBMS included in LTE –Release 8 and 9– and LTE-A –Release 10, 11 and 12– standards. It has presented the eMBMS features related to all layers, from the physical layer to the application layer. In particular, this chapter has described aspects of the eMBMS technology such as the eMBMS network elements introduced in the LTE logical architecture, the higher layer aspects of eMBMS services and use cases, the eMBMS-related channels within the LTE radio protocol architecture, eMBMS physical layer configuration and the scheduling of eMBMS data within LTE system.

This chapter has also identified some features included in other mobile broadcast systems that could be used in eMBMS for enhancing the performance of MBSFN deployments. They are the use of a dedicated carrier where all the subframes are dedicated for broadcast transmission and the use of MIMO schemes for enhance the broadcast service data rate. Both features have been analyzed in the performance evaluation of this chapter.

The performance results have shown that increasing the MBSFN area size always benefits coverage or allows employing a higher MCS. The use of a higher MCS, and the subsequent higher eMBMS data rate, entails a wider range of services per MBSFN area.

In addition, for dense mobile broadcast deployments, results have shown that MIMO schemes significantly increase the performance of broadcast transmissions. With an ISD of 500 m, the increase in maximum broadcast service data rate obtained using spatial multiplexing with two streams is around 59%. Consequently, future releases of LTE eMBMS should include the use of MIMO schemes to exploit their benefits.

Chapter 3

Optimum delivery of eMBMS services

As any communication system, LTE employs FEC techniques. FEC mechanisms rely on the transmission of repair information to protect from packet losses in underlying levels without a need for feedback, in such a way that the receiver can detect and possibly correct errors occurred during transmission. In particular, LTE uses Turbo codes as the FEC mechanism that works at the physical layer and, for eMBMS services, LTE can use Raptor codes as AL-FEC scheme. In short, AL-FEC schemes in eMBMS aim to enlarge the time interleaving duration of the information to take advantage of the time diversity of the mobile channel.

The drawback of sending additional repair data is not only a reduction in the system capacity, but also an increase of the system latency. The presence of latency in eMBMS affects the user experience by delaying the initial reproduction of the services and increasing the end-to-end delay. In eMBMS, multimedia content can be delivered as a streaming service or as a file download service to the end user [13]. These two type of services are of very different nature and have different QoS requirements in terms of residual error rate and latency constraints.

This chapter addresses the optimum delivery of streaming and file download services in eMBMS focusing on the trade-off between PHY-FEC and AL-FEC. Firstly, a review of the AL-FEC schemes in eMBMS is provided in Section 3.1. The provision of streaming services over eMBMS is investigated in Section 3.2, and the delivery of file download services is studied in Section 3.3. Finally, Section 3.4 concludes the chapter.

3.1 Forward error correction in eMBMS

LTE standard defines Turbo codes as the PHY-FEC to protect data against errors in the transmission over unreliable or noisy communication channels such as mobile wireless channel. PHY-FEC codes work at the bit level and are traditionally implemented as part of the radio interface for wireless communication systems. One of the main benefits of the use of turbo codes is that they can exploit CSI using soft decision decoding, thus achieving a high-performance. In soft decision decoding each bit is assigned a confidence value ranging from a minimum confidence zero to a maximum confidence one, which can be used for more reliable probabilistic decoding. However, in practice, due to on-chip memory and decoding complexity constraints, the maximum time interleaving depth is rather small. In LTE, the maximum time interleaving depth depends on the Transmission Time Interval (TTI) or subframe length, which is only 1 ms [79].

For unicast, a large time interleaving depth is not required due to the fact that p-t-p transmissions can adapt modulation and coding schemes for each individual user. Moreover, in case of a transport block reception with errors, the eNB can retransmit the same transport block using HARQ. Per contra, in eMBMS, the transmission of a transport block cannot be adapted for each individual user neither can be retransmitted. This can result in high loss rates for users with poor channel conditions [80]. As a consequence, PHY-FEC can be combined with AL-FEC for eMBMS transmissions in order to produce a more efficient overall system error protection [13].

In particular, 3GPP recommends the use of the systematic fountain Raptor code [81] as AL-FEC mechanism for the delivery of streaming and file download services. However, since Raptor codes were standardized, there has been significant progress in the design of FEC codes. Nowadays, RaptorQ [43] is the most recent member of Raptor codes family, providing exceptional protection performance and enhanced coding parameters. In the following, the main features of Raptor family codes are summarized.

It is worth noting that this chapter does not aim at comparing the performance between Raptor and RaptorQ codes, since this has been already performed in the literature [43, 82].

3.1.1 Raptor AL-FEC family codes

In general, AL-FEC codes are block codes that work with fixed-size symbols using erasure decoding. In erasure decoding, each symbol is either considered correctly received or lost. Then, it is necessary to indicate whether each packet is correctly received or not, such that the AL-FEC decoder observes a virtual erasure channel. AL-FEC aims to cope with these symbol erasures by adding some redundancy to the transmitted data.

Raptor codes are fountain codes, which are a class of erasure codes with the property that as many encoding symbols as desired can be generated by the encoder on-the-fly from the source symbols of a source block of data. In particular, Raptor codes are one of the first known classes of fountain codes with linear encoding and decoding time. In preparation of the encoding, a certain amount of data is collected within a FEC source block. Data of a source block are further divided into k source symbols of a fixed symbol size. Subsequently, the Raptor encoder generates n symbols from the $k < n$ source symbols, which are transmitted to the receiver. The decoder is able to recover the whole source block from any set of encoding symbols only slightly more in number than the source symbols.

The performance of a Raptor AL-FEC code can be described by the decoding failure probability as a function of the number of source and received symbols. Moreover, a crucial point for the robustness of an AL-FEC protected delivery is the transmission overhead, which is defined as the amount of the redundant information divided by the amount of source data and is equal to the fraction $(N-K)/K$ in terms of percentage, where N denotes the number of transmitted encoding packets and K denotes the number of the source packets.

The 3GPP standardized Raptor code [13] is a systematic code, which means that the original source symbols are within the stream of the transmitted symbols. The decoding failure probability of the standardized Raptor code can accurately be modeled by [35]:

$$P_{f_{Raptor}}(n,k) = \begin{cases} 1 & if\ n < k \\ 0.85 \cdot 0.567^{n-k} & if\ n \geq k \end{cases} \tag{3.1}$$

On the other hand, an enhanced Raptor code has emerged at Internet Engineering Task Force (IETF) in order to address the performance drawbacks of the standardized Raptor code, which is known as RaptorQ code. Similar to Raptor, RaptorQ is also a systematic code with significantly more efficient performance than the older Raptor code, in terms of superior flexibility, support for larger source block sizes and better coding efficiency. The enhanced design of RaptorQ addresses the Raptor code recovery performance limitations, resulting in a very close to an ideal fountain code performance described by [43]:

$$P_{f_{RaptorQ}}(n,k) = \begin{cases} 1 & if\ n < k \\ 0.01 \cdot 0.01^{n-k} & if\ n \geq k \end{cases} \tag{3.2}$$

3.1.2 Streaming and file download use cases

- Streaming services

AL-FEC can be used to provide streaming services over networks where packets losses are common. In the particular case of eMBMS, it is used to improve the coverage of video streaming services like mobile TV services.

Figure 3.1 shows the protocol stack of eMBMS including AL-FEC protection for the specific case of streaming services. AL-FEC coding is performed over Real-time Transport Protocol (RTP) packets. In video streaming applications, these RTP packets generally include H.264 Network Abstraction Layer (NAL) units and/or audio packets. In order to fit to the Maximum Transmission Unit (MTU) of the IP layer, the NAL units might be fragmented.

The application of AL-FEC to streaming media in MBMS is described in [13]. As depicted in Figure 3.1, three parameters have to be defined with regards to Raptor encoding: the protection period (T_{pp}), the code rate (k/n) and the source symbol size (T) measured in bytes. The Code Rate (CR) determines the amount of erroneous symbols than can be corrected at the application layer. Lower CRs increase not only the protection of AL-FEC, but also the amount of overhead that must be transmitted in the form of parity packets. On the other hand, T_{pp} determines the period of time over which the source blocks are transmitted. Longer protection periods imply higher time diversity and hence offer better robustness but at the cost of increasing the end-to-end delay and zapping time experimented by the user. This zapping time has a significant impact on the QoS perceived by the users. In order to reduce zapping time, several fast zapping techniques can be applied [13]. However, it must be noted that long protection periods greater than 10 s are not feasible in practice for streaming services, as they will involve long zapping times that would not be tolerated by end users even with fast zapping techniques [83]

The Raptor coding process is based on a systematic Raptor encoder, which uses a source block of k source symbols to generate the repair symbols. Then, first of all, a FEC source block is constructed from a set of RTP packets, exactly those generated in a T_{pp}. The size of the FEC source block is k times T. The selection of T_{pp} depends mainly on the desired delay and the memory available in the device. Therefore, all packets included in a single FEC source block are jointly protected. Afterwards, the Raptor encoder generates $n - k$ repair symbols of size T from the FEC source block according to the Raptor code rate.

After Raptor coding, two types of IP packets are obtained: FEC source packets and FEC repair packets. A source packet encapsulates original UDP packets while a repair packet encapsulates one or more repair symbols, which are generated in the FEC encoding process. Each source and repair packet

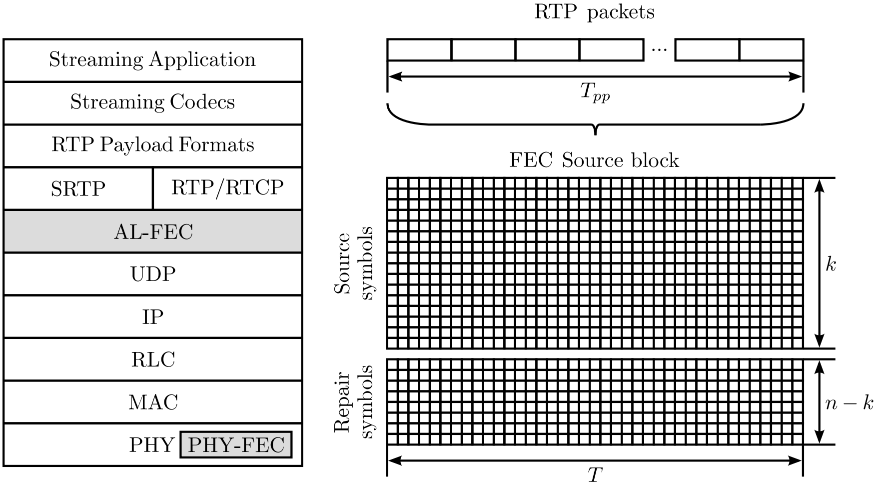

Figure 3.1: AL-FEC protocol stack for streaming services.

contains additional information for the packets-to-block mapping. This way, a receiver can use Raptor decoding to recover a source block if enough encoding symbols are received for that source block.

- File download services

AL-FEC can be very beneficial for file download services over broadcast channels where packet data losses are common. Its use can minimize the transmission duration and bandwidth requirement while ensuring a reliably delivery [84].

The file download delivery over eMBMS uses the FLUTE protocol [13], which is the most prominent protocol to deliver files in unidirectional environments. It is carried over UDP/IP, and is independent of the IP version and the underlying link layer used.

FLUTE is built on top of the Asynchronous Layered Coding (ALC) protocol instantiation, the base protocol designed for massively scalable multicast distribution [85]. ALC combines the Layered Coding Transport (LCT) building block to provide in-band session management functionality [86], a congestion control building block, and the FEC building block to provide flexibility [87]. The FEC building block allows for the choice of an appropriate FEC code to be used within ALC, including the possibility of sending the original data without FEC.

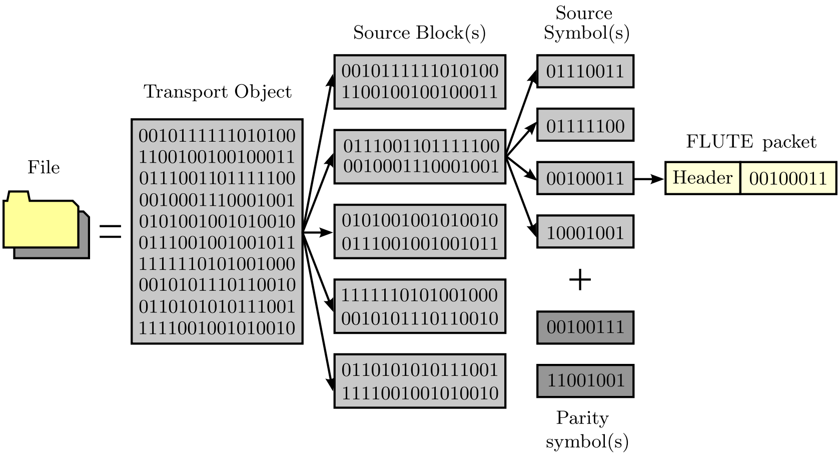

Figure 3.2: FLUTE blocking algorithm.

For FLUTE, the file is partitioned in one or several source blocks, as depicted in Figure 3.2 [84]. Each source block is split into source symbols of a fixed size. Symbol parameters are signaled in the session setup and are fixed for one session. Then, for each source block, FEC encoding can be applied to generate additional repair symbols. The collection of source and repair symbols is generally referred to as encoding symbols.

Each encoding symbol is assigned a unique Encoded Symbol ID (ESI). If the ESI is smaller than the number of source symbols, then it is a source symbol; otherwise it is a repair symbol. Symbols are either transmitted individually or concatenated and mapped to a FLUTE packet payload. The source block number, the ESI of the first encoded symbol in the packet and other file parameters are signaled in the FLUTE header. FLUTE packets themselves are then encapsulated in UDP and then distributed over IP MBMS bearers. Receivers collect correctly received FLUTE packets, and with the information available in the packet header and the file delivery session setup, the structure of the source block can be recovered. AL-FEC is very beneficial here, as it can be used to provide FEC protection to the file as an entity. An appropriate combination with PHY-FEC can result in very efficient file delivery services.

3.2 Delivery of streaming services

The optimization of the overall system FEC configuration becomes a cross-layer FEC configuration problem, which is more difficult to solve. This section addresses simultaneously the RRM problem and the trade-off between PHY-FEC and AL-FEC for streaming services. The main goal is to obtain the best configurations that allow the highest eMBMS service data rate when a fixed amount of resources is allocated for eMBMS. On the other hand, this section also studies how the conditions of the scenario in terms of SINR affect the selection of PHY-FEC and AL-FEC parameters. Finally, different alternatives of eMBMS scheduling are evaluated to determine how different services must be multiplexed within the AL-FEC interleaving time. For these investigations, extensive simulations have been carried out using the system-level simulator described in Annex A.2. The particular simulation configurations for these studies are provided in the following section.

3.2.1 Simulation assumptions

According to the simulation environment described in Section 1.5, simulations are divided into link-level and system-level simulations. For the simulations carried out in this section, we have added another type of simulations, named application-level simulations. The relation between system-level and application-level simulations is depicted in Figure 3.3. From the system-level simulations, we obtained a Protocol Data Unit (PDU) loss trace of 30 minutes for each simulated user. In the application-level simulations, the resulting RLC-PDU loss traces are applied to an IP multicast stream, where different AL-FEC parameters can be studied. For the sake of simplicity, simulations assumed ideal Raptor coding, that is, if the total number of IP packets correctly received within a protection period –source and repair packets– is greater than or equal to the number of source packets, then original data are recovered. In addition, a fixed IP packet size of 1024 bytes was used for both source and repair packets. Given this IP packet size and the packet headers, RTP packet size is 992 bytes, which implies a source symbol size T of 995 bytes.

System-level simulations were performed assuming the default configuration parameters shown in Table A.4. In this case, only the 19 central cells formed the MBSFN area. The multipath channel was modeled using the Extended Pedestrian A (EPA) and Extended Vehicular A (EVA) Power Delay Profiles (PDPs) for pedestrian and vehicular users, respectively. In order to reduce the complexity of the simulations, the multipath channel model was only used for those cells belonging to the MBSFN area, assuming frequency-flat fading channels for the remaining cells. The self-interference from the MBSFN was

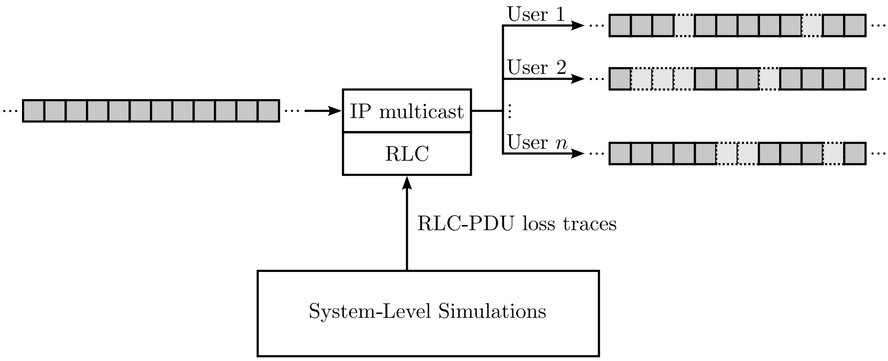

Figure 3.3: Application-level simulator architecture for streaming services.

modeled as defined in Section A.2.3 whereas the external interferences come from the cells surrounding the MBSFN area. For the sake of simplicity, active users were only dropped within the MBSFN area, while surrounding cells were working at full capacity, that is, the total transmission power was distributed uniformly within the whole bandwidth.

In these system-level simulations, MBSFN area and eMBMS service reception area were differentiated in the same way as in [88]. This was made in order to avoid a sharp drop in SINR for users in the border of the MBSFN area. For an MBSFN area of 19 cells, eMBMS service reception was studied within a radius equal to the ISD. Finally, pedestrian and vehicular users moved using the mobility model described in Section A.2.4 inside the eMBMS service reception area and bounced back at the coverage limit.

In the LTE system, eMBMS services were allocated 40% of resources, that is, four subframes per frame. MSP was set to 320 ms. With this configuration, results were obtained for several combinations of protection period, application layer code rate, and MCS at the physical layer. Each combination of these parameters corresponds to an available service data rate.

Protection periods ranged from 320 ms to 6.4 s in multiples of the MSP. At the application layer, several code rates from 1/5 up to 1[1] were used. With respect to the physical layer, only a set of the MCS shown in A.3 was assumed. At the physical layer, if the transport block size is larger than the maximum code block size –6144 bits– then it is fragmented in several turbo code blocks. In order to sum up, Table 3.1 presents all possible values for the main parameters used in the application-level simulations.

[1]AL-FEC CR equals to 1 means that AL-FEC is not applied and, therefore, only PHY-FEC is used as error protection mechanism.

Table 3.1: Main physical and application FEC parameters assumed in simulations.

Parameter	Value
MCS	QPSK: 120/1024, 193/1024, 308/1024, 449/1024, 602/1024 16-QAM: 378/1024, 490/1024, 616/1024
AL-FEC CR	1/5, 1/4, 1/3, 3/8, 2/5, 9/20, 1/2, 11/20, 3/5, 2/3, 7/10, 3/4, 5/6, 7/8, 23/25, 1
T_{pp} (s)	0.32, 0.64, 0.96, 1.28, 1.6, 1.92, 2.24, 2.56, 2.88, 3.2, 3.52, 3.84, 4.16, 4.48, 4.8, 5.12, 5.44, 5.76, 6.08, 6.4

3.2.2 Simulation results

Several metrics can be specified to obtain the performance of each configuration. In this study, three metrics were used: the Internet Protocol Packet Error Ratio (IP PER), the Erroneous Second Ratio (ESR), and the ESR5(20). The former represents the percentage of erroneously received IP packets. IP PER only accounts for the overall transmission errors experienced by the users and it does not represent the time distribution of errors, which also affects the QoS of a streaming service perceived by users. This can be taken into account with the other two metrics. ESR represents the percentage of seconds with errors and ESR5(20) represents the percentage of time intervals of 20 s with at most 1 s with errors (i.e., 5% errors).

- Performance assessment for different FEC configurations

This section investigates the trade-off between PHY-FEC and AL-FEC along with the influence of the protection period. Figure 3.4 shows an example of coverage performance of eMBMS for different AL-FEC configurations, i.e. application code rate and protection period combinations, for different MCSs. The left part corresponds to MCS 6 and the right part to MCS 7. In this case, ESR criterion was chosen and only vehicular users were deployed with an ISD scenario of 500 m.

In general, the coverage level depends on the MCS, obtaining better coverage for more robust MCS. Of course, higher robustness comes at the expense of a lower service date rate. According to the Figure 3.4, without AL-FEC –AL-FEC code rate 1– both MCS 6 and MCS 7 are unable to meet coverage

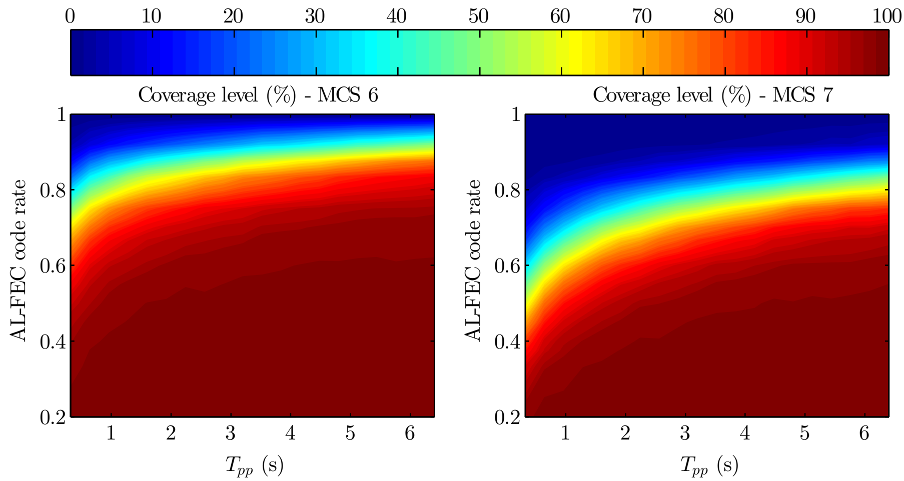

Figure 3.4: Coverage level vs. AL-FEC CR and T_{pp} for MCS 6 (left) and MCS 7 (right).

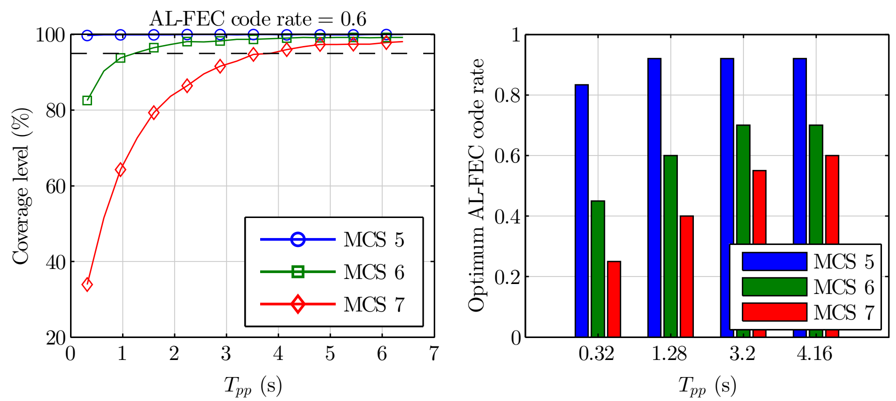

Figure 3.5: Coverage level vs. T_{pp} for several MCSs with fixed AL-FEC CR (left). Optimum AL-FEC CR vs. T_{pp} for several MCSs (right).

needs. However, the utilization of AL-FEC improves coverage. In particular, the coverage level increases with lower code rates and higher protection periods.

The left part of Figure 3.5 depicts the coverage level as a function of the protection period for several MCS with fixed AL-FEC code rate. These results reinforce the idea that coverage level increases with more robust MCSs and higher protection periods.

On the other hand, the optimum AL-FEC code rate is different depending on the MCS and protection period values. This is shown on the right part of Figure 3.5. As it can be seen, the optimum AL-FEC code rate is higher with larger protection periods and more robust MCSs. These results are tightly related with the maximum service data rate, as discussed below.

Figure 3.6 shows the maximum service data rate versus the protection period for several MCS using the ESR metric. Results are for both pedestrian and vehicular users. For each MCS, the maximum service data rate is obtained with the maximum Raptor code rate that guarantees a 95% coverage level. Note that a protection period of 0 s implies no use of AL-FEC and the maximum AL-FEC code rate can be different in the same curve depending on the protection period.

As Figure 3.6 shows, AL-FEC is required if MCSs is greater than 4. In these cases, the maximum service data rate increases with longer protection periods. For this scenario, the best option is to use the MCS 5 for pedestrian users whereas, for vehicular users, the optimum MCS –among MCS 5, 6, or 7– depends on the protection period. From these results, two conclusions can be drawn. First, for the pedestrian case at some point longer protection periods do not entail any advantage. Second, the benefits of AL-FEC are higher for vehicular users as compared with pedestrian users. The reason for this is that the performance of AL-FEC increases with the speed of the users since it is

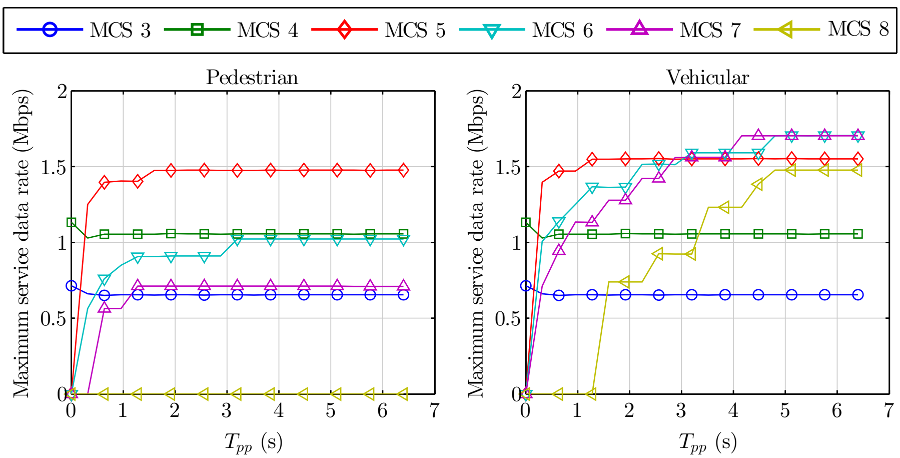

Figure 3.6: Maximum service data rate vs. T_{pp} for different MCSs with ESR metric for pedestrian (left) and vehicular (right) users.

possible to exploit the temporal diversity within the protection period. This fact also explains the lower maximum service data rate of pedestrian users.

- FEC performance over different error metrics

This section studies AL-FEC performance over different error metrics such as IP PER, ESR and ESR5(20). Given a protection period, the maximum service data rate was obtained choosing the best combination of MCS and AL-FEC code rate.

Figure 3.7 shows the maximum service data rate for pedestrian (left) and vehicular (right) users. Note that the ESR curves of Figure 3.7 correspond to the upper envelope of the curves shown in Figure 3.6. The same conclusions drawn from Figure 3.6 can be made from Figure 3.7. However, the more restrictive the quality criterion, the lower the maximum service data rate reached and the higher the improvement achieved using AL-FEC.

Moreover, longer protection periods result in a higher maximum service data rate. However, the introduction of application layer error recovery mechanisms increases the zapping time. This trade-off must be taken into account in the system design, provided that zapping times greater than 2 s are annoying for the end user. Note that zapping time is equal to 1.5 times the protection period without using fast zapping techniques. If the parity data are transmitted before source data, the zapping time can be reduced. This reduction depends on the AL-FEC code rate. Therefore, assuming zapping times less than 2 s as

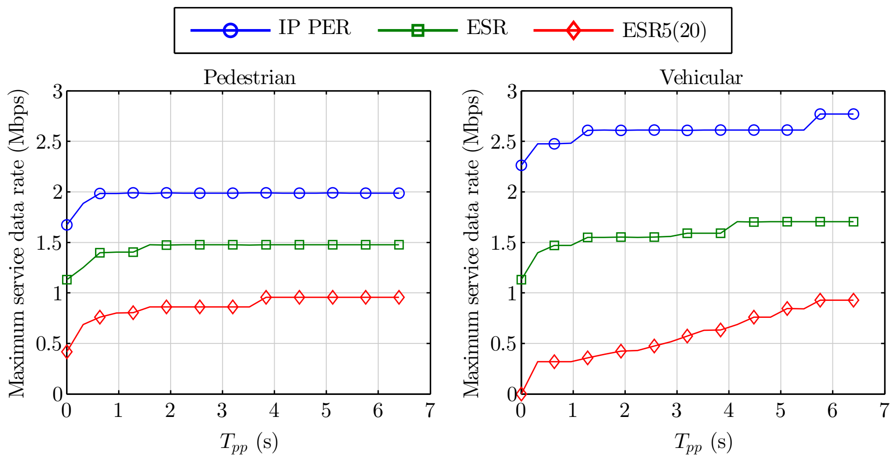

Figure 3.7: Maximum service data rate vs. T_{pp} for several metrics for pedestrian (left) and vehicular (right) users.

Table 3.2: Maximum data rate comparison considering both use and no-use of AL-FEC with T_{pp} of 1.28s.

Pedestrian			
Quality criterion	**Maximum data rate (kbps)**		**Gain (%)**
	No AL-FEC	**AL-FEC**	
IP PER	1672.80	1990.63	19.00
ESR	1131.60	1402.63	23.95
ESR5(20)	418.20	802.38	91.86
Vehicular			
Quality criterion	**Maximum data rate (kbps)**		**Gain (%)**
	No AL-FEC	**AL-FEC**	
IP PER	2263.20	2609.25	15.29
ESR	1131.60	1549.63	36.94
ESR5(20)	0	355.25	Inf

acceptable, Table 3.2 shows the AL-FEC performance results using a protection period of 1.28 s, which corresponds to a zapping time about 1.92 s. These results are compared with the case in which AL-FEC is not used.

Finally, Table 3.3 summarizes the best combination, in terms of maximum service data rate, of MCS and AL-FEC code rates for different quality criteria and type of users. These results correspond to a protection period of 1.28 s. Two are the main conclusions that can be drawn from these results. First, vehicular users need, in general, less protection than pedestrian users. Second, with a more restrictive quality criterion it is required a higher protection both at physical and application layers. Obviously, the maximum data rate is lower when the quality criterion is more restrictive.

- Effect of SINR distribution over FEC performance

This section assesses the performance of AL-FEC when varying the SINR distribution. With this aim, two scenarios with different ISDs –500 and 1500 m– were analyzed. For the sake of simplicity, results are only shown for vehicular users.

The average SINR of users with an ISD of 500 m is approximately 2 dB higher than with an ISD of 1500 m. As summarized in Table 3.4, best SINR

Table 3.3: The best configurations for pedestrian and vehicular users with T_{pp} of 1.28 s.

Quality criterion	**Pedestrian**		**Vehicular**	
	MCS	**AL-FEC CR**	**MCS**	**AL-FEC CR**
IP PER	6	0.88	7	0.92
ESR	5	0.83	5	0.92
ESR5(20)	4	0.70	2	0.83

Table 3.4: The best configurations for different ISDs for vehicular users with T_{pp} of 1.28 s.

ISD 500 m			
Quality criterion	**MCS**	**AL-FEC CR**	**Maximum data rate (kbps)**
IP PER	7	0.92	2609.25
ESR	5	0.92	1549.63
ESR5(20)	2	0.83	355.25
ISD 1500 m			
Quality criterion	**MCS**	**AL-FEC CR**	**Maximum data rate (kbps)**
IP PER	5	0.7	1182.13
ESR	3	0.84	594.13
ESR5(20)	2	0.26	110.25

conditions allow using lower levels of protection. Provided that the amount of resources reserved for eMBMS is the same, this robustness implies that the maximum service data rate is higher for smaller ISD scenarios.

- Study on the effective time interleaving

So far, results have been obtained assuming that one service channel occupies all the resources allocated to eMBMS with an MSP value of 320 ms. This section studies the effect of eMBMS scheduling on AL-FEC performance. The assessment is performed using the example shown in Figure 3.8, where four streaming channels are multiplexed within the protection period using different values of the MSP. In that example, the protection period is 1.28 s. The figure shows that the higher the MSP, the lower the resources dedicated to eMBMS control. However, a high MSP reduces time diversity. This section analyzes this trade-off.

As explained above, the performance of AL-FEC improves with the user velocity, since it is possible to exploit the temporal diversity within the protection period. This is why this section focuses on a vehicular scenario. Besides, two different protection periods –1.28 and 5.12 s– and several MSPs were analyzed. ESR metric was used.

Figure 3.9 shows the coverage level as a function of the AL-FEC code rate and the MSP. MCS 7 was used for a protection period of 1.28 s (left) and MCS 8 for a protection period of 5.12 s (right). On the one hand, using low MSPs implies more resources dedicated to eMBMS signaling. For example, with a protection period of 1.28 s, 16 MSI are transmitted using an MSP of 80 ms, whereas only 4 MSI are required with an MSP of 320 ms. However, the results show that, for a given AL-FEC code rate, the lower the MSP, the higher the coverage level. Indeed, using a low MSP allows for a better exploitation of temporal diversity since each eMBMS channel transmission is divided into several intervals within the protection period. Despite the additional signaling overhead, this entails a larger effective interleaving and a better performance. In addition, the effect of the MSP is more significant for longer protection

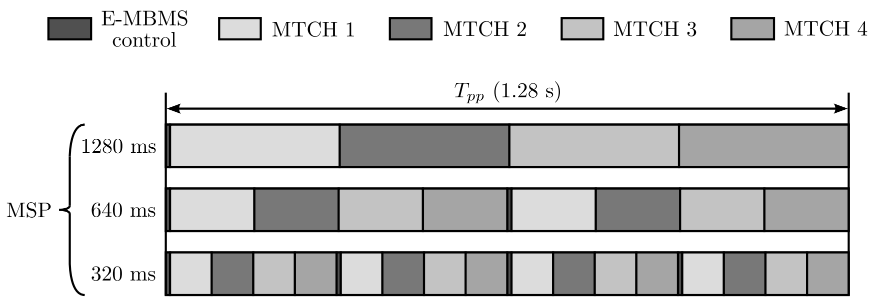

Figure 3.8: Example of different eMBMS services multiplexing within the T_{pp} for several MSP values.

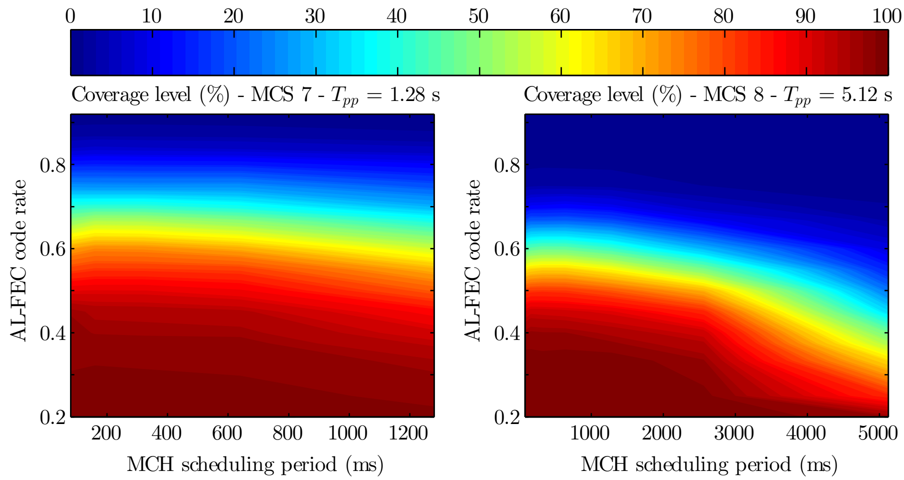

Figure 3.9: Coverage level vs. AL-FEC CR and MSP for MCS 7 with T_{pp} of 1.28 s (left) and MCS 8 with T_{pp} of 5.12 s (right).

periods since there is more room for time interleaving. It is worth noting that this effect depends on the speed of the user, since for low mobility users there is little temporal diversity. In fact, similar simulations were performed for pedestrian users and this effect was not noticeable.

3.3 Delivery of file download services

This section investigates the file download delivery method in eMBMS, which uses the FLUTE protocol [13]. In particular, this section analyses the duration of the transmission required to guarantee the correct file reception, which depends on the number of resources allocated to eMBMS and on the MCS.

3.3.1 File download service delivery procedures

The file download service in the eMBMS consists of three phases [84]:

1) Service advertisement phase: in which the service is announced and set-up by the network and the users discover the service.

2) Initial eMBMS file transmission phase: in which the source data file and a fixed pre-configured amount of AL-FEC parity data are initially transmitted with a p-t-m connection within the subframes allocated to eMBMS.

3) Post-delivery repair phase: in which users not able to decode the file after the initial eMBMS transmission are served by default via p-t-p connections to complete the reception of the file. In case too many users fail to receive the file, it is also possible to use a p-t-m connection.

This section discusses the initial eMBMS file transmission phase and the error repair phase from an overall radio resource management perspective. In order to achieve an efficient delivery it is needed to optimize the initial eMBMS file transmission including the trade-off with the error repair phase. A temporal diagram of both phases is shown in Figure 3.10. For a more detailed description of the procedures involved we refer to [13].

- Initial eMBMS file transmission phase

In this phase the BM-SC must configure the transmission parameters statistically to ensure that the file is successfully received by the worst-case user contemplated, such that the desired file acquisition probability is reached (percentage of users that receive the file).

The reliability of the eMBMS transmission of a file is again given by the combination of the MCS and the amount of Raptor parity data transmitted. The selection of FEC parameters must be adequately performed to ensure that the file is successfully received by, in this case, 95% of users. In order to achieve this, there are two possible options:

- Transmit the file using only eMBMS until the 95% acquisition probability is reached (referred to as conventional file delivery).
- Transmit data with eMBMS during the time required to achieve a certain acquisition probability and then use a repair phase that will serve the remaining users (referred to as hybrid approach).

The decision must be made considering the existing trade-off between the acquisition probability of the initial eMBMS transmission phase and the delivery time.

- Post-delivery repair phase

The purpose of this phase is to repair erroneous received files after the initial eMBMS transmission. Terminals not able to recover the file notify the minimum set of data packets required to repair the file or simply the total number of correctly received packets [13]. This information is useful to determine if p-t-p or p-t-m retransmission is preferred. This information is sent to a file repair server that processes repair requests and sends responses in a

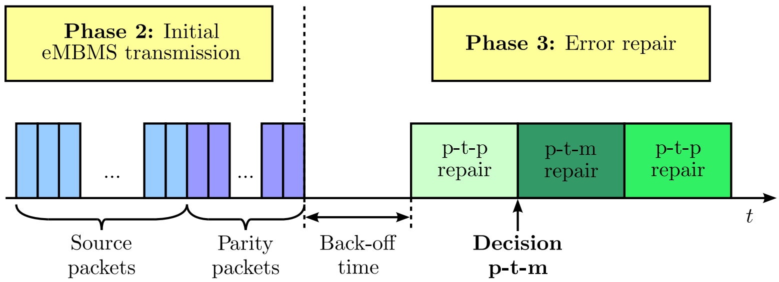

Figure 3.10: eMBMS file download service. Initial eMBMS transmission and repair phase.

single Transmission Control Protocol (TCP) session using the HTTP [13]. In particular, file repair requests are processed using an HTTP GET command.

To avoid congestion, error reporting messages from terminals can be distributed over time within a back-off window and across multiple repair servers. The back-off window should be large enough to prevent congestion, but should not unnecessarily increase the duration of the repair phase.

As mentioned before, terminals start the repair phase using dedicated p-t-p connections, but if the number of active users in this phase is high enough it is possible to employ a p-t-m connection with eMBMS. However, during the initial file transmission there is no communication between the terminals and the server. Then, once the initial eMBMS transmission is finished, the server does not have any information about the number of users that have not received the file and the amount of repair data needed by each of them. This information can be estimated in the beginning of the post-delivery repair session.

The decision of performing a p-t-m repair transmission should be taken as soon as possible once a representative number of error reporting messages has been collected. Usually, it is recommended to take this decision once the 10% of the back-off window has elapsed [89]. With the aim of serving users with bad channel conditions, the new eMBMS transmission should use a more robust MCS. The duration of this transmission would depend on the amount of repair data requested by the users at the time of the decision. Once the p-t-m repair session is completed, a new p-t-p repair session can be initiated if needed as there is not guarantee that users will receive the data transmitted with eMBMS. In this case, the length of the second back-off window should be smaller than the first one, since a lower load on the repair server can be expected.

The hybrid approach consisting in a combined eMBMS and p-t-p operation increases its efficiency –as compared with other conventional approaches– when the fraction of static users is large. In these scenarios of low mobility, to further extend the duration of the initial eMBMS, file transmission does not necessarily improve the probability of successful reception of the file.

3.3.2 Conventional file delivery

Next we study the performance of using eMBMS transmissions to provide file delivery services considering different type of users and file sizes. The eMBMS transmissions were performed using single-cell organization, that is, without creating any SFN. Concerning the mobility of users, static, pedestrian (3 km/h) and vehicular (30 km/h) users were simulated. With respect to the file sizes, 2 and 5 MB were considered.

The performance of eMBMS depends on the number of allocated subframes. Obviously, eMBMS users increase their throughput and QoS with more subframes. To assess the QoS experienced by users, a file download time was defined as the time required ensuring a correct file downloading of more than 95% of users in the cell. As an example, Figure 3.11 represents the file download time needed to transmit a file of 2 MB to vehicular users as a function of the MCS for one to six subframes per frame allocated to eMBMS. As expected, file download time is lower with more subframes allocated to eMBMS, although the absolute impact decreases with the number of subframes added.

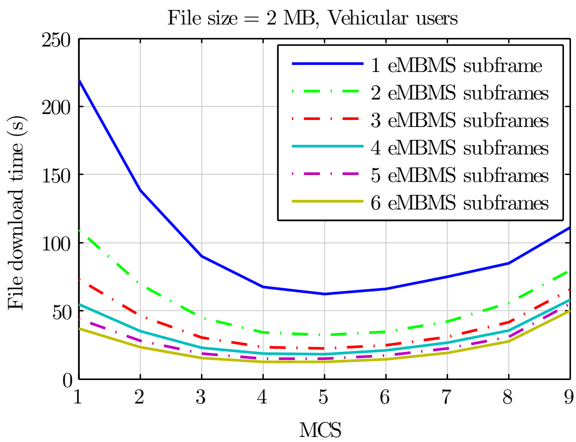

Figure 3.11: File download time vs. MCS with different number of allocated eMBMS subframes for vehicular users.

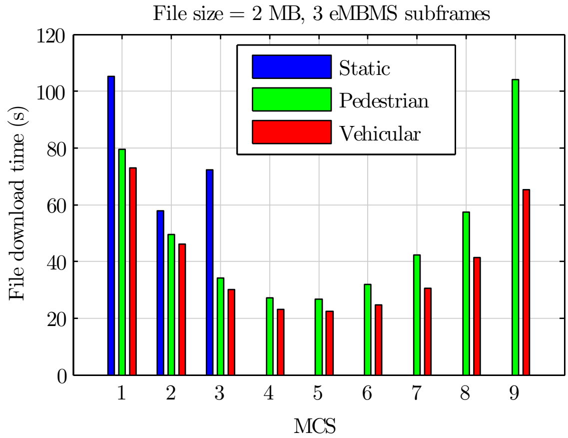

Figure 3.12: File download time vs. MCS with different number of allocated eMBMS subframes for static, pedestrian and vehicular users.

Concerning the MCS selection, initially the file download time decreases with higher MCSs. Nevertheless, this trend reaches its minimum value for a given MCS, and then it rises again for higher MCS. In the particular scenario assumed in this section, the optimum MCS is 5. The reason for this behavior is that higher MCSs require higher SINR values to be effective. If the MCS is too high, then coverage is reduced and the time to satisfy cell-edge users increases. It is worth noting that the same conclusion was obtained for a file size of 5 MB.

Concerning the effect of user speed, Figure 3.12 compares the performance of static, pedestrian and vehicular users. It was assumed the same file size of 2 MB and 3 subframes allocated for eMBMS. Figure 3.12 shows that users' mobility increases channel diversity, which results at the end in a better performance. Concerning static users, 95% of coverage can only be achieved when using robust MCSs, i.e. less than or equal to 3, since they cannot benefit from diversity gain.

Of course, the inclusion of eMBMS in the same carrier will have an impact on the performance of unicast users. The higher the number of subframes allocated to eMBMS, the lower the average quality perceived by unicast counterparts. Figure 3.13 shows the cell throughput for an increasing number of unicast users per cell, assuming full buffer traffic, when all subframes are allocated to unicast services, i.e. 10 subframes. The cell throughput increases with the number of users. However, this trend tends to saturate from 50 users. In fact, with only 10 and 20 users, cell throughput is 95%-98% of its maximum, respectively. Therefore, it can be assumed that already for 10-20 users the multiuser diversity is close to its limit. From this result, it was decided to

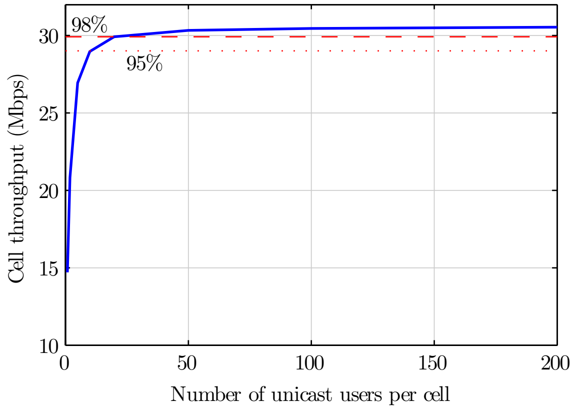

Figure 3.13: Cell throughput vs. number of unicast users per cell.

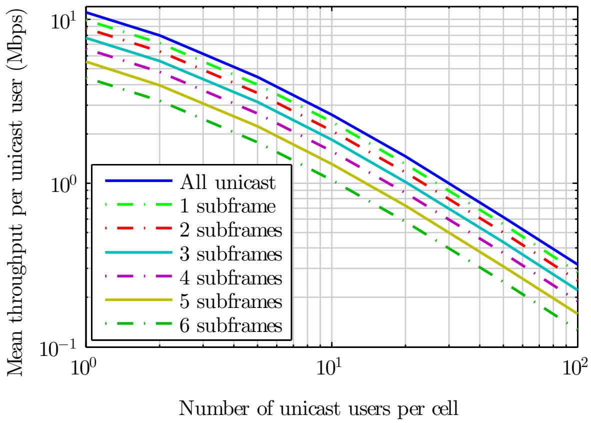

Figure 3.14: Average throughput per unicast user vs. number of unicast users per cell with different number of subframes allocated to eMBMS.

assess unicast degradation with eMBMS considering from 1 to 50 unicast users per cell.

Figure 3.14 shows the average throughput per unicast user depending on the number of subframes allocated to eMBMS. The degradation, as compared with a situation without eMBMS transmissions, is proportional to the number of eMBMS subframes, that is to say, the reduction in the average throughput per unicast user coincides with the percentage of subframes used for eMBMS transmissions, as expected. Moreover, this degradation does not depend on the number of unicast users in the cell.

3.3.3 Hybrid approach

This section studies the transmission of the same 2 MB file when the users interested in receiving that file are static. In this situation hybrid transmission is especially interesting since some users could be hardly reached by eMBMS transmissions. Indeed, only the most robust MCSs are able to deliver the file to all users in the cell in this particular case. Thus, this section compares the time required to serve 95% of users interested in receiving the file in the next three operation modes:

1) Transmit the file to interested users using p-t-p connections.

2) Transmit the file using only one eMBMS transmission using MCS 1.

3) Transmit the file using the hybrid approach.

In this particular case in which all users are static, it is quite simple to configure the initial eMBMS transmission phase. This is because a user located within coverage range receives correctly all data, whereas a user that is located out of coverage does not receive any data. In this way, with MCS 1 the acquisition probability is 100% and, when the MCS increases, the acquisition probability decreases. Provided this scenario, the hybrid approach is as follows:

- The file is initially transmitted with eMBMS during the exact time required to deliver the data in the MCS-specific coverage area.

- The remaining users are served with p-t-p connections in the repair phase.

Two different type of users were assumed in this study: file download users and unicast users. The former were those interested in receiving the file and the latter were those interested in other unicast services. The simulations considered a set of 30 unicast users plus a variable number of file download users. The left part of Figure 3.15 shows the file download time required for the three operation modes, when one subframe is allocated for eMBMS transmissions. For all cases, the file download time is measured as the time required ensuring a correct file downloading of more than 95% of the file download users. It is observed that with few file download users in the cell, p-t-p transmission is the best option. These p-t-p transmissions can be even more efficient for cell-edge users due to the gain provided by HARQ retransmissions and MIMO. However, starting from a certain number of users (13 in this particular case), it is

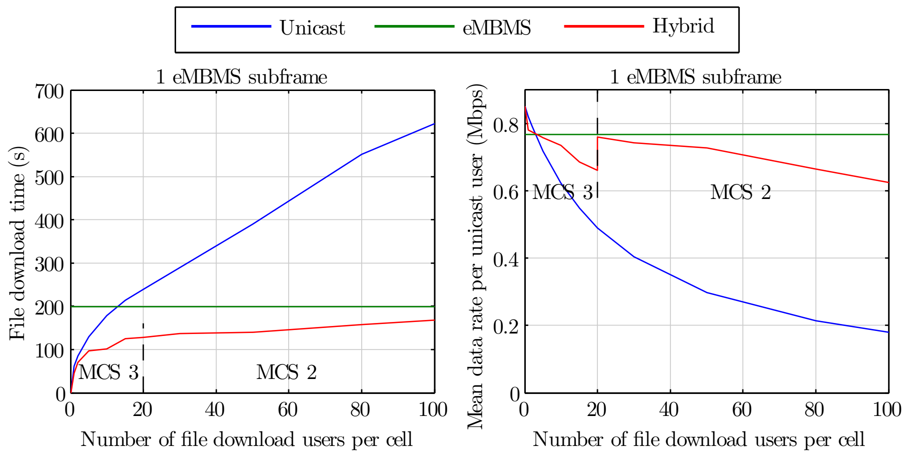

Figure 3.15: File download time (left) and mean data rate per unicast user (right) vs. number of file download users per cell.

more efficient to use eMBMS to serve the file. The figure shows that the best option to minimize the file download time is the hybrid approach, obtaining a gain in terms of reduction of time for every number of file download users. The gain increases until the crossing point of the two reference curves using unicast and eMBMS transmission separately –with 13 file download users–. This is the point with maximum gain, 40.3% of reduction of file download time in this case. After this point, the gain decreases with the number of file download users per cell. The mean reduction of file download time achieved with the hybrid approach is 27.4%. Moreover, from the operator's point of view it is easier to implement the hybrid approach than being constantly checking the number of active users per cell to switch from unicast to eMBMS transmission.

For the hybrid approach, the optimum configuration of the initial eMBMS transmission varies with the number of file download users. As observed on the left part of Figure 3.15, if there are few users in the cell –up to 20 users–, the optimum eMBMS configuration selects MCS 3. For more than 20 users, the optimum configuration changes and the MCS 2 is the best option. This is because the higher the number of users the easier to find users located out of coverage and, hence, it is more efficient to use a more robust MCS.

Together with the file download time, throughput degradation introduced by the multiplexing of eMBMS services was also studied. The right part of Figure 3.15 shows the values of throughput for each of the three operation modes simulated. As it was previously shown in Figure 3.14, when using only eMBMS the reduction in the average throughput per unicast user coincides with the percentage of subframes allocated to eMBMS, which is in this case a reduction of 10%. The right part of Figure 3.15 shows that this is the best option for almost every number of file download users in the cell, being the worst case using unicast transmission. The hybrid transmission introduces a higher degradation in the average throughput as compared with the case with only use of eMBMS because of the repair phase. However, this reduction could be acceptable due to the improvement of the file download time.

The results analysed in this section correspond to the particular case of allocating 1 subframe per frame to eMBMS transmissions. However, the number of subframes can vary from 1 to 6. For each one of these possible values, Table 3.5 shows the file download time assuming eMBMS transmission and the mean file download time reduction with the hybrid approach, and Table 3.5 shows the average throughput reduction of the unicast users for the three operation modes considered in this study. Obviously, the higher the number of eMBMS subframes, the lower mean file download time reduction with the hybrid approach. The reason is that, in these conditions, eMBMS is a very good option in terms of file download time. However, the average throughput reduction is very high, in comparison with the case with only one eMBMS subframe. There is a trade-off between the unicast throughput quality and the file download time.

3.4 Conclusions

eMBMS specifications allow for an optimum delivery of broadcast services, providing flexibility in the configurations of FEC mechanisms to adjust the broadcast transmission to the different types of eMBMS services. This chapter has investigated the trade-off between PHY-FEC and AL-FEC within the delivery of both streaming and file download services. In these studies, we have assumed that eMBMS services are provided in a frequency carrier shared with unicast traffic.

On the one hand, this chapter has investigated the optimum delivery of streaming services over an MBSFN area of 19 cells. Firstly, it has been compared several AL-FEC configurations with different protection periods and code rates with the transmission of streaming services without AL-FEC protection. This chapter has also studied the effect of several AL-FEC parameters on system performance in several scenarios with different average SINRs and the effect of the time multiplexing of different services within the AL-FEC time interleaving.

Table 3.5: File download time with eMBMS and mean file download time reduction with the hybrid approach.

eMBMS subframes	File download time with eMBMS [s]	Mean time reduction with hybrid [%]
1 subframe	198.78	27.35
2 subframe	99.39	20.52
3 subframe	66.26	15.51
4 subframe	49.7	13.26
5 subframe	39.76	10.36
6 subframe	33.13	8.58

Table 3.6: Average data rate reduction of unicast users with unicast, eMBMS and hybrid file delivery.

eMBMS subframes	Average unicast user data rate reduction [%]		
	Hybrid	eMBMS	Unicast
1 subframe	17.91	10	58.23
2 subframe	29	20	
3 subframe	39.12	30	
4 subframe	48	40	
5 subframe	55.51	50	
6 subframe	62.4	60	

In the first assessment, several conclusions were obtained. The first one is that the coverage of streaming services increases with the usage of AL-FEC and, then, a higher maximum service data rate can be obtained if AL-FEC is used. However, this gain depends on the parameter settings, the user type scenario, and the quality criterion. The results show that the larger the protection period, the greater the maximum service data rate. However, large protection periods produce an excessive zapping time that affects the QoS and it is not recommended for streaming services. For example, when using a protection period of 1.28 s, which gives a zapping time lower than 2 s that can be considered as acceptable, gains of 23.95 and 36.94% for ESR were obtained using AL-FEC for pedestrian and vehicular users, respectively. This shows that the gain is greater in scenarios with high mobility users. Finally, the more restrictive the quality criterion, the lower the maximum service data rate achieved, although the improvement achieved using AL-FEC is higher in these criteria (91.86% using an ESR5(20) for pedestrian users).

In the other assessments, a higher protection at both physical layer and application layer must be applied in larger ISD scenarios in order to obtain the maximum service data rate. Obviously, the maximum service data rate in this case is lower. Finally, a higher interleaving between different channels within the protection period improves the coverage level as it is possible to exploit better the temporal diversity. Also, the effective interleaving is enlarged. However, this effect depends on the speed of the user, since for low mobility users there is little temporal diversity.

On the other hand, this chapter has investigated the optimum delivery of file download services assuming single-cell eMBMS operation. In particular, some results regarding the transmission period required to guarantee the correct reception of a file has been presented . At the beginning, increasing the MCS reduces this file download time. However, in case of the use of a too-high MCS, transmission errors make retransmission necessary and deteriorate the system performance. Given the simulation scenario proposed in this chapter, the optimum MCS is 5. Once unicast and broadcast users are jointly considered, the inclusion of eMBMS in the same carrier affects the performance of unicast users. As expected, this degradation is proportional to the number of subframes allocated to eMBMS. Actually, the reduction in the mean user throughput matches exactly the percentage of subframes allocated to eMBMS, which simplifies the decision making.

Finally, this chapter has offered a complementary analysis of file delivery using hybrid configurations. In this analysis, LTE unicast transmissions could be employed for error repair of a first phase with eMBMS transmissions. The hybrid delivery has proven to be the most efficient configuration in terms of file download time, although this will further damage unicast performance.

Chapter 4

Use of eMBMS for vehicular safety applications

The latest developments taking place over the past few years in most areas of wireless communication and wireless networks, in combination with the technological development of the automotive industry, have paved the way for a totally new approach to vehicular safety, which integrates multiple equipment and technologies in one autonomous and intelligent vehicle. Within this concept, the term ITS refers to a new set of information and communication technologies that allow improving traffic safety while reducing traffic congestion and pollution. ITS implies introducing new elements in the car, mainly related with wireless communications, computing and sensing capabilities. Vehicles are already sophisticated computing systems, with several computers onboard, which collect information about themselves and the environment and exchange information with other nearby vehicles and the infrastructure. It is worth noting that, in this new scenario of intelligent cars, communication plays a crucial role.

The CEN and ETSI finalized during 2013 a basic set of standards necessary for the implementation and deployment of C-ITS systems as requested by the European Commission [46]. This set of standards is mainly based on the IEEE 802.11p access technology for ITS communications, which are defined as ITS Frequency band 5.9 GHz dedicated for safety related applications (ITS-G5) communications by ETSI. The system is well suited to active road safety use cases due to its very low delays and communication range of several hundred meters. However, the channel congestion experienced in dense scenarios and its decentralized ad-hoc nature is motivating the research of other technologies, like cellular networks, as alternatives for ITS communications.

However, although LTE promises better levels of quality in terms of throughput and latency compared to 3G systems, it is not clear whether LTE networks can support vehicular safety applications in an efficient manner by means of unicast transmissions. Similarly to IEEE 802.11p, there is a scalability problem related to the fact that messages belonging to vehicular safety applications have to be delivered to potentially all the vehicles in a certain geographical area, and with stringent delay requirements. If the unicast transmission mode is used, the amount of resources required for the delivery of vehicular safety messages might result in elevated costs for the MNOs as well as for the service providers (e.g. car manufacturers). In this context, the utilization of broadcast technologies, like eMBMS, has been identified as a possible solution to solve the scalability problem of vehicular safety applications in cellular networks.

This chapter addresses the provision of vehicular safety services over LTE cellular networks comparing both unicast and broadcast delivery modes in terms of capacity, latency and cost. The capacity and latency comparison of both transmission modes is performed through several system-level simulations whereas the cost comparison is performed through a cost modeling analysis. In addition, this chapter addresses open issues to support ITS applications over current eMBMS architecture. The rest of the chapter is organized as follows. Firstly, Section 4.1 summarizes the vehicular communications for ITS and the applications and use cases. Section 4.2 presents the communication characteristics and features of LTE cellular networks within the vehicular communications system context. Section 4.3 describes the simulation assumptions. Simulations results are discussed in Section 4.4 whereas a cost analysis of the impact of different transmission modes is discussed in Section 4.5. Finally, Section 4.6 includes the main conclusions of this chapter.

4.1 Vehicular communications for C-ITS

4.1.1 ITS communication architecture

The European ITS communication architecture is described in [90]. The architecture comprises four main ITS communication components, which are ITS vehicle station, ITS roadside station, ITS central station and ITS personal station. An ITS station consists of an Application Unit (AU) and a Communication and Control Unit (CCU). From a network stack perspective, an AU contains the communication protocol layer while a CCU covers the lower layers up to the transport layer.

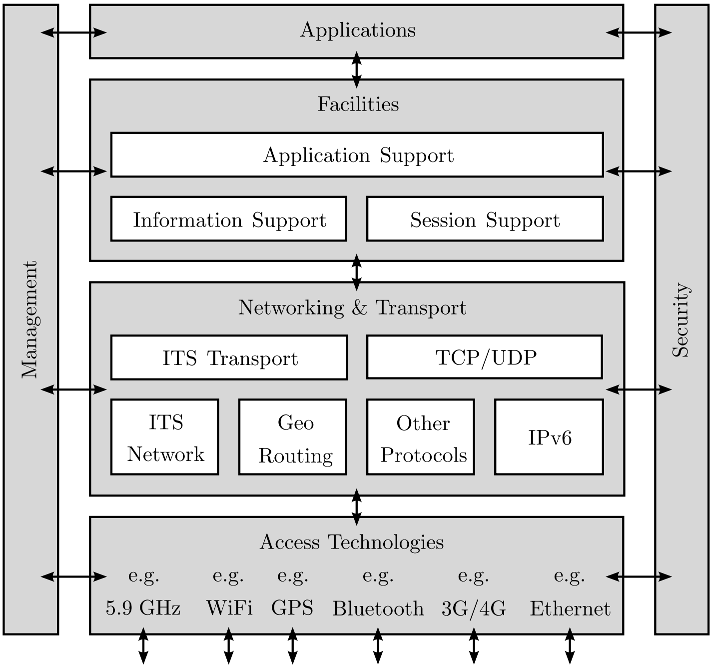

Figure 4.1: ITS station reference architecture.

Figure 4.1 shows the protocol stack of an ITS station specified in [90]. It follows the principles of the OSI model and basically consists of six components: the four stacked layers "Access technology", "Network and Transport", "Facility" and "Applications", plus the two cross-layer components "Management" and "Security".

- The "Access technology" layer comprises the physical and data link layer of various communication technologies as shown in Figure 4.1. The access technologies are not restricted to specific type of media, although most of the access technologies are based on wireless communications. The communication technologies are used for communications inside of an ITS station and for external communication. The complete communication stack is included for some specific non-ITS communication technologies such as cellular 3G/4G or Bluetooth.

- The "Network and Transport" layer comprises protocols for data delivery among ITS stations and from ITS stations to other network nodes, such as network nodes in the core network (e.g. the Internet). ITS network protocols particularly include the routing of data from source to destination through intermediate nodes and the efficient dissemination of data in geographical areas. ITS transport protocols provide the end-to-end delivery of data and, depending on requirements of ITS facilities and applications, additional services, such as reliable data transfer, flow control and congestion avoidance. A particular protocol in the ITS network and transport layer is the Internet Protocol version 6 (IPv6). The usage of IPv6 includes the transmission of IPv6 packets over ITS network protocols, dynamic selection of ITS access technologies and handover between them, as well as interoperability issues of IPv6 and Internet Protocol version 4 (IPv4).

- The “Facilities” layer provides a collection of functions to support ITS applications and to help managing the system. The facilities provide data structures to store, aggregate and maintain data of different type and source. As for communication, ITS facilities enable various types of addressing to applications, provide ITS-specific message handling and support establishment and maintenance of communication sessions. An important facility is the management of services, including discovery and download of services as software modules and their management in the ITS station.

- The “Applications” layer refers to the different ITS applications and use cases for road safety, traffic efficiency, infotainment and business.

- The “Management” cross-layer is responsible for configuration of an ITS station, cross-layer information exchange among the different layers and others tasks.

- The “Security” cross-layer is responsible for security and privacy on the different layers of the protocol stack and manages for example station identities and security credentials.

Next section describes the applications and use cases for vehicular communications defined in the ETSI ITS standard [47].

4.1.2 Applications and use cases

The number of possible applications that arise from the connectivity between ITS stations (i.e., vehicles and traffic infrastructure) is enormous and, obviously, each application has a different set of requirements. The applications for vehicular communications –ITS applications– can be divided into three main categories or classes that comprise applications with similar requirements. The three main classes of ITS applications are cooperative road safety, cooperative traffic efficiency and, cooperative local services and global Internet services. The three different classes and their requirements are presented in a compact form in Table 4.1.

- Cooperative road safety

The main objective of the cooperative (or active) road safety applications is the improvement of road safety. These ITS applications are related to driving assistance and can be divided into two types: those associated with Cooperative Awareness (CA) and those associated with Road Hazard Warning (RHW).

On the one hand, the use cases related to the CA applications are emergency vehicle warning, slow vehicle indication, intersection collision warning and motorcycle approaching indication. On the other hand, the ones related to RHW applications are emergency electronic brake lights, wrong way driving warning, stationary vehicle –due to an accident or a vehicle problem–, traffic condition warning, signal violation warning, roadwork warning, collision risk warning and decentralized floating car data with different cases –hazardous location, precipitations, road adhesion, visibility or wind.

The cooperative road safety application class is by far the most demanding one due to the message frequency and the very stringent latency requirements. In many use cases, the minimum frequency of the periodic messages can be 10 Hz, whereas the latency time use to be less than 100 ms.

Table 4.1: ITS applications class and requirements.

Application class	**Objective**	**Service frequency (Hz)**	**Latency requirement (ms)**
Cooperative road safety	Road safety and collision avoidance	10-20	50-100
Cooperative traffic efficiency	Improvement of traffic fluidity	1-5	100-500
Cooperative local services and global Internet services	Infotainment, comfort and commercial use	On demand	Greater than 500

- Cooperative traffic efficiency

The improvement of the traffic fluidity is the primary objective of traffic management application class. These ITS applications can be divided into two types: speed management and cooperative navigation.

On the one hand, the use cases related to speed management are regulatory/contextual speed limits notification and traffic light optimal speed advisory. On the other hand, the ones related to cooperative navigation are traffic information and recommended itinerary, enhanced route guidance and navigation, limited access warning and detour notification and in-vehicle signage.

This application class has not performance requirements as critical as road safety applications. The message generation frequency can vary from 1 to 5 Hz and the latency is in the range within 100-500 ms.

- Cooperative local services and Global Internet services

The applications related to cooperative local services and global Internet services advertise and provide on-demand information to passing vehicles on either a commercial or non-commercial basis. The main components of this class are Infotainment, comfort and vehicle life cycle management.

The cooperative local services are associated to location-based services, which consist of applications such as point of interest notification, automatic access control and parking management, ITS local electronic commerce and media downloading. On the other hand, the global internet services are divided into two types: communities services and ITS station life cycle management. Applications such as insurance and financial services, fleet management and loading zone management are related to the first type, and, applications such as vehicle software/data provisioning and update, and vehicle and Road Side Unit (RSU) data calibration, are associated to the latter type.

The cooperative local services and global Internet services application class has very relaxed latency requirements. The maximal latency time is usually above 500 ms.

This chapter focuses on the cooperative road safety applications due to they are the most exigent vehicular applications in terms of the amount of data to be transmitted –service frequency– and the latency requirement.

4.1.3 Cooperative road safety applications

As mentioned before, CA applications and RHW applications are the two different type of applications related to cooperative road safety. This section describes both types in detail.

- Cooperative awareness applications

CA applications are based on the periodic interchange of status data among neighboring vehicles. According to ETSI, this data interchange between vehicles is based on the transmission of Cooperative Awareness Messages (CAMs) [91].

CAMs are used to exchange information of presence, position, as well as basic status. By receiving CAMs, the vehicle is aware of other vehicles in its neighborhood area as well as their positions, movement, basic attributes and basic sensor information. At the receiver side, it is assumed that reasonable efforts can be taken to evaluate the relevance of the messages and the information. This allows ITS stations to get information about its situation and act accordingly.

Table 4.2 contains the use cases based on CAMs and the corresponding requirements [91]. As it can be seen, most of the use cases require a minimum transmission frequency of 10 Hz and a maximum end-to-end latency of 100 ms. In addition, ETSI defines several rules for CAM generation:

- The maximum time interval between CAM generations is 1 s.
- The minimum time interval between CAM generations is 100 ms.
- A CAM must be generated when absolute difference between current heading –towards North– and last CAM heading is greater than 4°.

Table 4.2: Overview of the CA use cases.

Use case	**Minimum frequency (Hz)**	**Maximum latency (ms)**
Emergency vehicle warning	10	100
Slow vehicle indication	2	100
Intersection collision warning	10	100
Motorcycle approaching indication	2	100
Collision risk warning	10	100
Speed limits notification	1 to 10	100
Traffic light optimal speed advisory	2	100

- A CAM must be generated when distance between current position and last CAM position is greater than 4 m.
- A CAM must be generated when absolute difference between current speed and last CAM speed is greater than 0.5 m/s.
- The generation rules are checked every 100 ms.

If these rules were not applied, a vehicle waiting at a traffic light would transmit 10 CAMs per second with the same location information. With the application of these rules, the same vehicle would generate a CAM each 1 s thus helping avoid network congestion.

According to the message format specified by ETSI, the status information provided by a CAM is divided into four containers: basic, high-frequency, low-frequency and special vehicle containers [91]. Both basic and high-frequency containers are mandatory whereas low-frequency and special vehicle containers are optional. In addition, the size of containers depends on several optional fields. This entails that the CAM payload is of variable size. For example, the maximum payload size of a CAM with only mandatory containers is around 50 bytes whereas it increases up to 250 bytes when including the low-frequency container.

In addition to this CAM format, ETSI specifies the formats of security header –96 bytes– and certificate –133 bytes– used for securing ITS-G5 communications. A remaining question regarding the transmission of CAMs via cellular networks is the inclusion of the security overhead. Some works assume that no security payload is needed as it should be possible to provide access control via Subscriber Identity Module (SIM)-cards [52]. However, the addition of security overhead could be needed in order to provide end-to-end security.

- Road hazard warning applications

RHW applications are event-based applications composed of multiple use cases. The main purpose is to alert the rest of the vehicles in the network about an unexpected situation. According to ETSI, the Decentralized Environmental Notification Message (DENM) is used by RHW applications for this purpose [92].

DENMs are triggered by specific events on the road and must be disseminated with a certain transmission frequency to as many vehicles located within the relevance area as possible. As they are sent depending on events, they do not have a fixed schedule as CAMs. The general processing procedure of a RHW use case is as follows:

- Upon detection of an event that corresponds to a RHW use case, the ITS station should immediately send a DENM message to other ITS stations located inside a geographical area and which are concerned by the event.
- The transmission of a DENM is repeated with a certain frequency.
- This DENM broadcasting persists as long as the event is present.
- The termination of the DENM broadcasting is either achieved once the event disappears after a predefined expiry time, or by an ITS station that generates a special DENM to inform that the event has disappeared.
- ITS stations, which receive the DENMs, process the information and decide to present appropriate warnings or information to the users in the vehicle, as long as the information in the DENM is relevant for the ITS station.

Concerning to the area where DENMs must be disseminated, ETSI defines two different areas related to a RHW [92]: the relevance area and the destination area. The former is the minimum area where the RHW must be disseminated as the ITS stations located within such area are concerned by the road hazard. The relevance area can be described as a geometrical area, a road topology area or a specific traffic direction. The latter is the geographical area in which RHWs are disseminated through the LTE network in the case discussed in this chapter. The destination area can be defined by geometrical shapes: circular, rectangular or elliptical. While the destination area is not necessarily identical with the relevant area, it should cover the entirety of the relevance area. Figure 4.2(a) shows and example where a vehicle detects a RHW and the relationship between the relevance area and the destination area for that RHW is shown in Figure 4.2(b). In this example, the relevance area is certain distance within the upstream traffic of the vehicle position whereas the destination area is a rectangle covering road topology.

The message format described by ETSI [92] specifies that a DENM is divided in four containers: management, situation, location and “à la carte” containers. Only the management container is mandatory. Similarly to CAM, the DENM payload size depends on optional containers and optional fields. As an example, the maximum payload size of a DENM with only the management container is around 45 bytes. If both situation and location containers are included, the DENM payload size ranges between 250 and 1500 bytes.

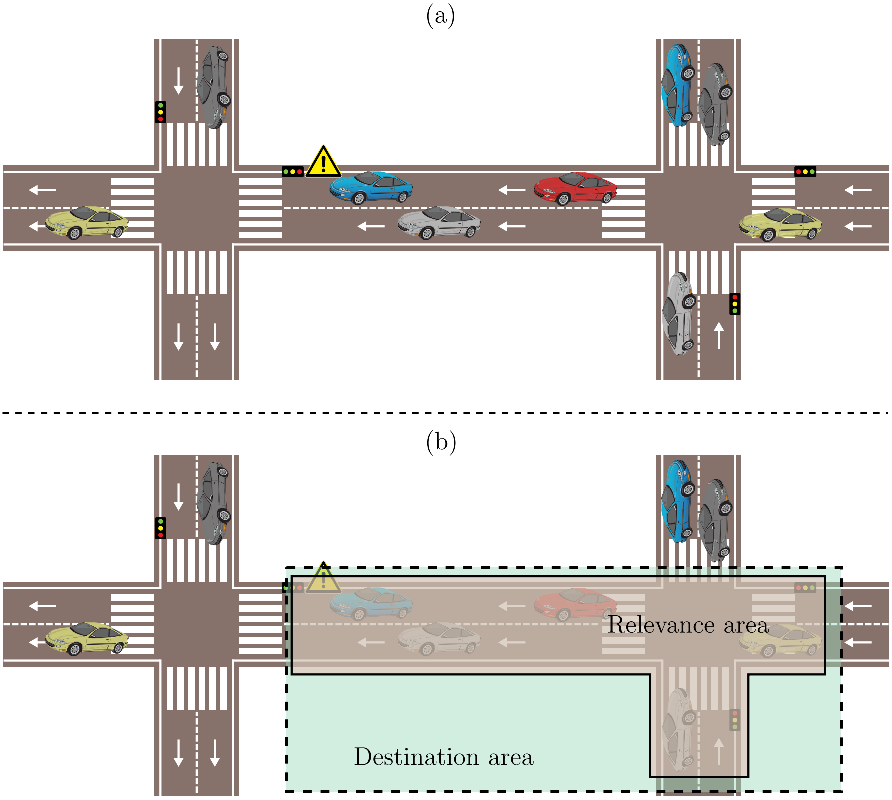

Figure 4.2: (a) A vehicle detects a RHW. (b) Relationship between the relevance area and the destination area of this RHW.

4.2 Delivery of vehicular safety applications over LTE networks

LTE cellular networks offer two modes of data transmission: unicast and eMBMS delivery. For the provision of vehicular applications, both modes require an ITS backend server that receives messages from the vehicles and the traffic infrastructure, processes the information, and redistributes it to the vehicles and the traffic infrastructure [48, 50] This section summarizes the main features of both modes with special emphasis over eMBMS operation.

On the one hand, unicast delivery must be used for the uplink and is an optional mode for the downlink communication. Figure 4.3 shows an example

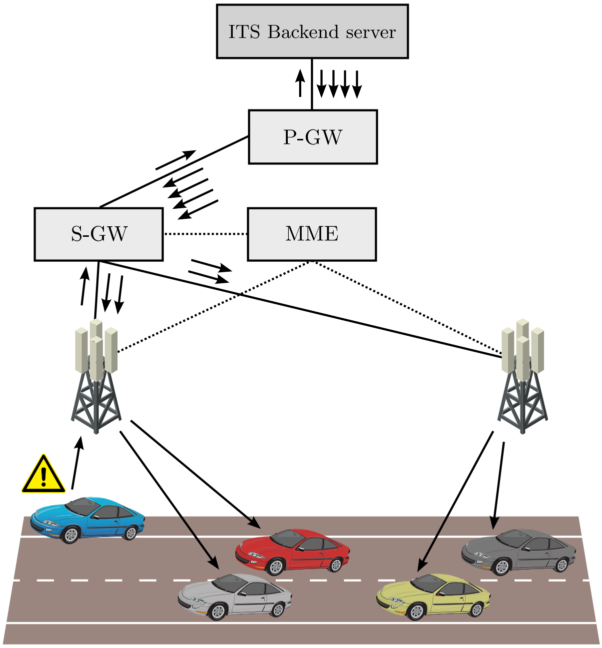

Figure 4.3: Unicast delivery mode of RHW applications.

of a RHW application where a vehicle sends a DENM with its identification, event cause, and position via the cellular network to the ITS backend server. This information is then distributed to all vehicles in the neighborhood. The ITS backend server needs location information about every single vehicle in order to identify the vehicles potentially interested in the RHW information within a certain area. One option is that ITS server uses the location information provided by the CAMs that are sent in the uplink. Another option is to make use of grid-based methods in which the vehicles send location information updates to the ITS server every time they enter a new cell within the grid-area [52].

On the other hand, the eMBMS delivery mode can be used exclusively for the downlink distribution of ITS messages. In this case, all vehicles belonging to the broadcast area are addressed collectively, rather than individually. In the exemplary broadcast scenario represented in Figure 4.4, the ITS backend server addresses the BM-SC to distribute data via eMBMS. To this purpose, the ITS backend server has to identify the broadcasting area that is better suited to the RHW information. It is important to note that eMBMS can

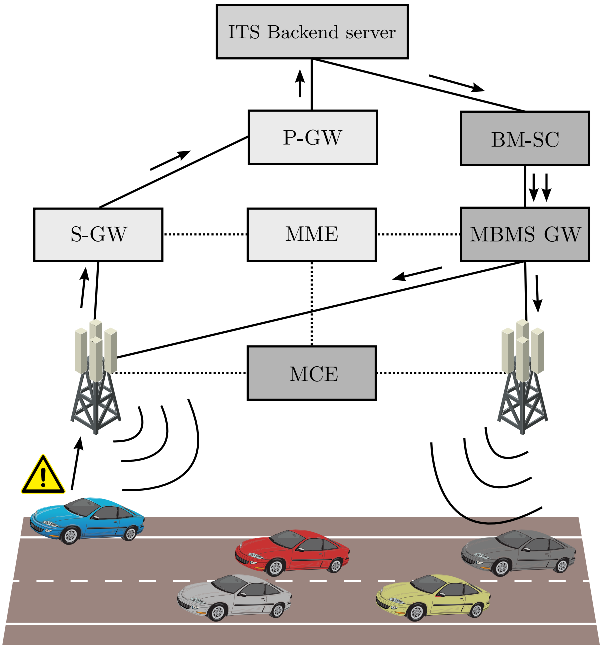

Figure 4.4: Broadcast delivery mode of RHW applications.

maintain different broadcast areas, which consist of any set of cells specified by the MNO.

The main difference compared with the unicast scenario is that the whole broadcast area is addressed instead of a single user. In this manner, a significant amount of resources can be saved due to the fact that every message is only transmitted once per broadcasting area instead of once per vehicle. At the same time, the location information of potential recipient vehicles is not needed in the broadcast case, and therefore, an important amount of resources is also saved in the uplink.

On the other hand, broadcast delivery mode prevents the information from being personalized on a user basis. As a result, the vehicle has to filter the relevant information out of all the information delivered in the broadcasting area. Larger broadcasting areas offer potentially greater resource savings but increase the processing that has to be done in the vehicle.

In other words, unicast delivery requires extensive processing in the ITS backend server in order to select the receivers of each message reducing the processing requirements in the vehicle, whereas eMBMS delivery shifts the processing efforts from the ITS backend server to the end user, thus distributing the computational burden.

4.2.1 eMBMS architecture for vehicular safety services

As Figure 4.4 shows, there are several functional entities related to the eMBMS architecture involved in the delivery of ITS services using broadcast transmissions. Readers can remember the functionalities of the eMBMS architecture described in Section 2.1.1.

In the specific case of applications for vehicular communications, the content provider entity corresponds with the ITS server. Currently, there is not any specification concerning the interface between the content provider and the BM-SC. Therefore, the configuration of the ITS backend server shall require the common work of operators and car manufacturers. Due to the relevance and tight interactivity of the ITS backend server and the BM-SC, it is likely that both entities would be integrated in the same physical device.

Another aspect to be considered is the logical location in the IP domain of the ITS backend server. From a latency point of view, it would be beneficial that the ITS backend server was located within the operator network, with a private IP address valid in the operator domain. However, this alternative would prevent cars belonging to different operators from getting connected. Therefore, the ITS server should be located in the Internet, with a public IP address so that it is reachable by all MNOs. In order to reduce the latency, each ITS server must be regional-wise, with a limited number of route hops until the MBMS GW in the mobile network. Note that the MBMS GW, the BM-SC and the content provider are entities with public IP address. This dissertation proposes that the BM-SC and the content provider –ITS backend server– share the same IP being reachable by all operators. Vehicles will subscribe to the service in the same entity, which shall distribute the relevant and filtered information to the same areas covered by different operators. The functionality of this new node, the one that merges BM-SC and ITS server duties, is described in the following section.

4.2.2 Functionality of the BM-SC/ITS server node

According to the specifications [71], the BM-SC is responsible for the following sub-functions in E-UTRAN: membership function, session and transmission function, proxy and transport function, service announcement function, security function and content synchronization for eMBMS.

New functionalities must be added to support ITS applications. More specifically, the new entity must receive information from vehicles –instead of

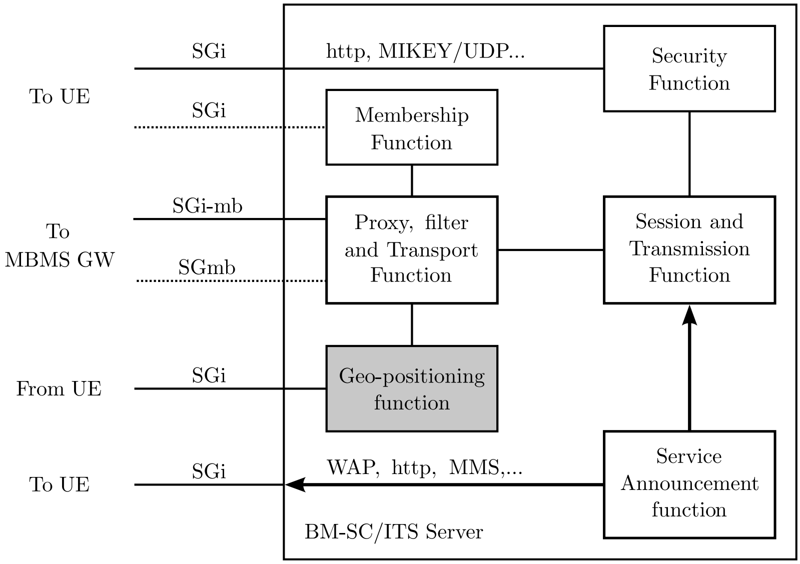

Figure 4.5: Main functionalities of the proposed BM-SC/ITS backend server node.

only sending the information as in the BM-SC– and filter the data streams according to the geo-localization of the vehicles. Therefore, a new geo-positioning function must be included to allow for this smart filtering. This functionality would be in charge of selecting the broadcasting area for each message to be delivered. In addition, it is worth stressing again here that all communication with the UE and the MBMS GW is made through a conventional IP connection that requires the appropriate Domain Name System (DNS) resolution in the UE side and a complete registration process. The new characteristics of the BM-SC/ITS backend server node are depicted in Figure 4.5.

4.2.3 Vehicular safety services configuration for eMBMS delivery

As it has been described in Section 2.1.2, an MBMS user service is the entity in charge of providing the service to the end user and controlling its activation or deactivation. For road safety applications, two are the MBMS user services to be defined: one for the CA service and another for the RHW service.

A single MBMS user service can contain several multimedia objects or streams, which might require multiple MBMS sessions [93]. Each MBMS session might be associated with more than one MBMS bearer and a set of delivery parameters, including the broadcasting area. By using multiple MBMS sessions, the same MBMS user service can transmit different contents in each broadcasting area of the network. In this manner, the relation between broadcasting areas and content is transparent for the vehicles, i.e., they just activate the reception of the service and receive the content according to their location.

The BM-SC controls the content related to vehicular services to be delivered in each broadcasting area by establishing a separate MBMS bearer for each vehicular service content data flow. All MBMS bearers of the same MBMS user service share the same TMGI but contain a different flow identifier. The BM-SC allocates the flow identifier during the MBMS Session Start procedure and initiates a separate session for each content data flow. Besides, for IP multicast support, the MBMS GW allocates an IP multicast address based on the TMGI and flow identifier.

In order to receive an MBMS service, vehicles must subscribe to the service and, whenever data are available, the BM-SC starts the session. The session is first announced via the MBMS control channels and, after that, the data channel can be established and used. This implementation is resource-efficient in terms of transmission power since vehicles are able to perform discontinuous reception to save battery power. Nevertheless, the "Session Start" and "MBMS Notification" phase take some time that makes this procedure not be recommended for time-critical traffic warnings.

To enable a broadcast channel with minimal transmission delays, a continuous eMBMS service for cooperative road safety should be configured [50]. In this manner, the vehicle only has to join the eMBMS service at the beginning of each session (e.g. when the vehicle is started) and receives continuously the data until the session ends (e.g., when the vehicle is shut down). By using a continuous eMBMS service it is possible to minimize the delays associated to the "Session Start" and "MBMS Notification" procedures.

Although current eMBMS standard specifies two delivery methods for the MBMS user services, namely download and streaming, other delivery methods may be added beyond the current release of specifications. In principle, ITS content could be provided through eMBMS using the download delivery of binary files. However, this method is not suitable for services with very stringent delay requirements, such as those of ITS. Thus, the provision of vehicular safety service content using eMBMS could only be performed by defining a new delivery method addressed for time-critical requirements. In next sections, we have assumed the use of this new delivery method.

4.2.4 Vehicular safety services scheduling for eMBMS delivery

The eMBMS control information provided by LTE networks to inform about the eMBMS scheduling has been described in Section 2.1.5. It is worth remembering that the MCE provides to eNBs a semi-static allocation of radio resources for each MCH belonging to an MBSFN area and also provides the scheduling period –MSP– where all eMBMS data traffic channels must be multiplexed.

The eNB can allocate eMBMS resources in a persistent or in a dynamic manner. If the resources for eMBMS are allocated persistently, the continuously maintained data channel would allow for the immediate transmission of ITS information. While this approach minimizes the delay for the downlink transmission, it might lead to a waste of resources when the amount of road safety services information to be transmitted is lower than the amount of resources allocated to eMBMS. A solution to this problem is that the eNB performs a dynamic scheduling of eMBMS resources. An example of this dynamic scheduling for the CA services is shown in Figure 4.6, where 15 vehicles transmit one CAM each 100 ms. The proposed configuration consists in adapting the resource allocation to the amount of data to be transmitted in each scheduling period, whose lowest value is 80 ms. The empty subframes not used for eMBMS in each scheduling period can be used for unicast services in order to avoid a waste of resources. It should be noted that, although this approach results in a more efficient resource utilization, it might increase the delay of road safety applications. In particular, the maximum latency of a message in the downlink would be about 80 ms, which corresponds to the worse situation in which the message arrives at the beginning of the previous scheduling period. In the depicted example, the worst case is when the CAM gets into MTCH buffer at $t_0 + 80$ ms and it is transmitted in the first eMBMS data subframe of the next MSP at $t_0 + 162$ ms with a delay of 82 ms. It is worth noting that this delay corresponds to the downlink delay. The most common requirement for these vehicular applications is that the end-to-end delay should be less than 100 ms. That end-to-end delay consists of the uplink delay, the processing delay at nodes and the downlink delay.

4.3 Simulation assumptions

The assessment of the vehicular safety services delivery in LTE networks was performed using the system-level simulator presented in Section A.2. However, unlike the other simulations performed in this dissertation, this analysis focused on a motorway scenario deployment described next.

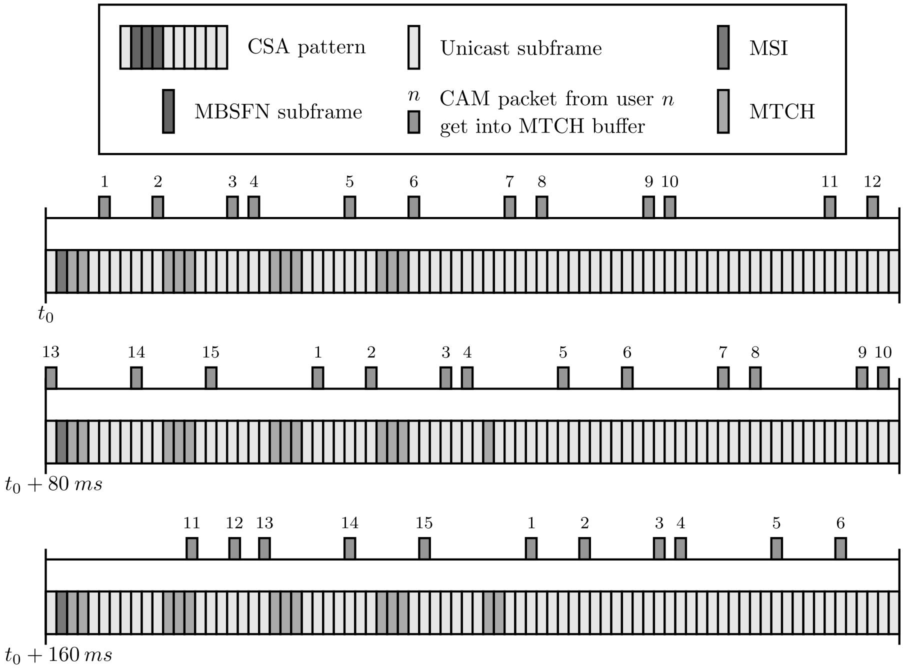

Figure 4.6: An example of a dynamic scheduling of eMBMS resources for the delivery of CA service.

4.3.1 Motorway scenario

Figure 4.7 shows the motorway scenario assumed in simulations. The LTE cell layout in the motorway scenario is shown in Figure 4.7(a). It consists of several base stations arranged along a motorway stretch of 20 km. The LTE deployment is based on a frequency carrier of 800 MHz and two different alternatives for the ISD, 10 and 5 km. In the former case, a total of 2 sites may cover the total road length whereas the latter uses four different sites to cover the 20 km of road length. Each one of the sites has two sectors, which covers both directions of the motorway. Besides, according to real deployments, antenna height is 20 m, the antenna azimuth is 3°, the antenna downtilt is 6°and the distance from the center edge of the highway to the site is 35 m.

Figure 4.7(b) shows the motorway layout for simulations. This road environment consists of three lanes per direction with a central median and both external and internal berms. Each lane has a width of 3.5 m. The widths of

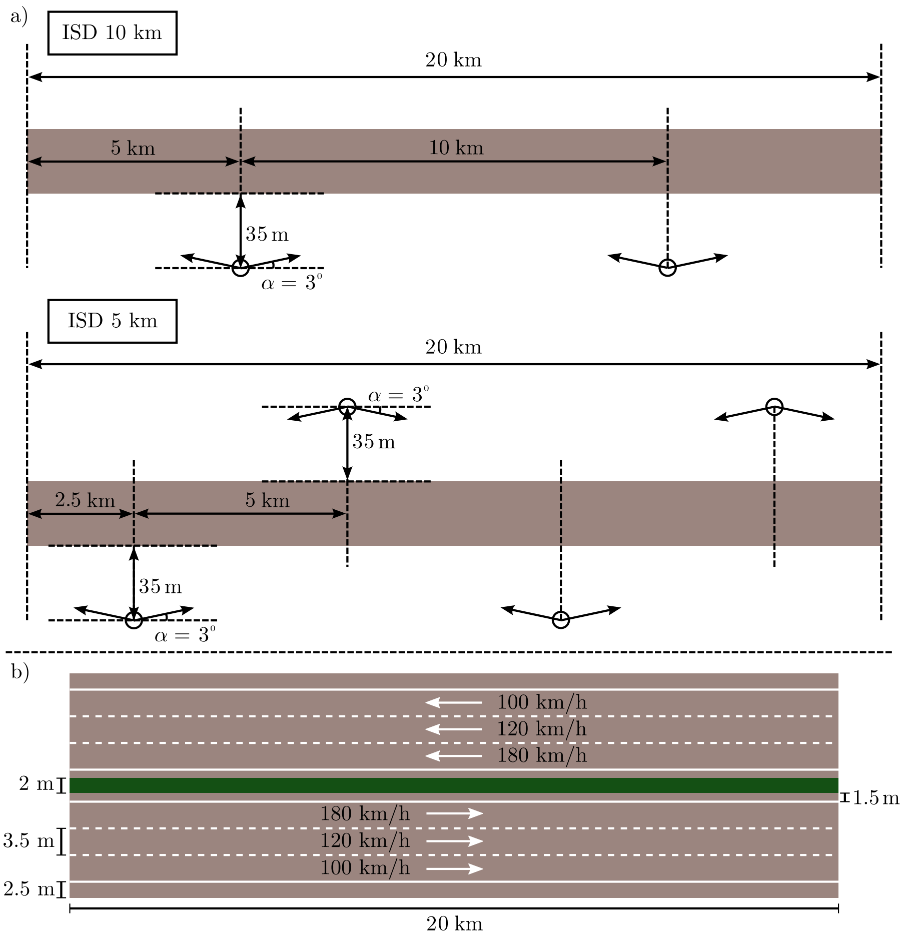

Figure 4.7: (a) LTE cell layout in the motorway scenario and (b) motorway layout.

the external and internal berms are 2.5 and 1.5 m, respectively, and the median width is 2 m. The total motorway width is 31 m.

4.3.2 Configuration parameters and assumptions

Table 4.3 summarizes the configuration parameters, which follow the ITU guidelines [94], applied in the assessment of the delivery of vehicular safety messages in LTE networks.

Table 4.3: Simulation parameters and assumptions for the assessment of the delivery of vehicular safety messages.

System parameters	**Value**
Bandwidth	10 MHz FDD
Central frequency	800 MHz
Tx/Rx antennas	Unicast: MIMO 2/2 eMBMS: SIMO 1/2
eNB transmit power	46 dBm
eNB antenna gain	14 dBi
eNB cable loss	2 dB
Vehicle antenna gain	2 dBi
Vehicle cable loss	0.2 dB/m (2 m of cable length)
Vehicle implementation loss	5 dB
Vehicle noise figure	7 dB
Path loss	Based on Rural Macro-cell (RMa) model [94]: $PL = PL_{LoS} \cdot P_{LoS} + PL_{NLoS} \cdot (1 - P_{NLoS})$
Shadowing parameters	Standard deviation (σ): 6 dB Correlation distance (d_{corr}): 100 m
Multipath channel model	EVA PDP
Control channels overhead	Unicast: 2 symbols (6 downlink assignments) eMBMS: 1 symbol
CQI reporting period	20 ms (CQI wideband)
Scheduling algorithm	Proportional fair

A LTE FDD system with a 10 MHz system bandwidth was assumed, however, only downlink simulations were carried out. For the purpose of the study, it was assumed that the vehicular safety services are deployed in an empty LTE system in order to obtain the system capacity for these communications. Although other unicast traffic with different QoS requirements may be influenced by the ITS traffic, we assume that the highest priority is given to vehicular safety services and therefore there would not be any impact of the other traffic on ITS behavior, which is the focus of the study performed in this chapter. This fact was also checked with proper simulations and we preferred to remove any other unicast service for the sake of simplicity. This assumption is the same as the referenced work performed in [52].

Vehicles are randomly dropped over the six different lanes –three lanes per direction– with different speeds. As Figure 4.7 shows, three different speeds were assumed for the three different lanes per direction. These speeds are 100, 120 and 180 km/h. Each user keeps the same lane and its speed is constant during all the simulation time. Besides, when a vehicle arrives at the lane end, it reappears at the beginning of the lane. Simulations are dynamic and handover processes occur due to mobiliey of vehicles.

With respect to the density of vehicles, it is based on the scenario itself, that is, the road parameters and the safe distance between vehicles. According to the European directive on minimum safety requirements [95], road users driving personal vehicles should under normal conditions maintain a minimum distance from the vehicle in front of them equivalent to the distance travelled by a vehicle in two seconds. Then, vehicles keep a security distance equivalent to 2 s in simulations. Using this assumption, in a motorway stretch of 20 km, there can be a maximum of 1610 vehicles.

4.3.3 Vehicle safety data traffic models

The simulations considered two different types of data traffic models in the context of automotive applications, CA applications based on CAM and RHW applications based on DENM.

- CA applications

In the study for CA applications, it was assumed that every vehicle sends messages in the uplink to a backend server with a transmit rate of 10 CAMs/s, as defined by ETSI. In order to illustrate the system behaviour with lower transmit rates, additional results for a transmit rate of 2 CAMs/s are also provided. In order to determine the CAM payload size, it it assumed that each CAM contains a high-frequency container –50 bytes– and a secure header –96 bytes–. A low-frequency container –201 bytes– and a certificate –133 bytes– are included each 500 ms and 1 s, respectively. Taking this consideration into account, the CA service data rate in uplink is:

$$DataRate_{CA}\,(\text{Bytes/s}) = N_{CAMs/s} \cdot 50 + 2 \cdot 201 + N_{CAMs/s} \cdot 96 + 1 \cdot 133, \quad (4.1)$$

where $N_{CAMs/s}$ is the number of CAMs transmitted in one second. With these assumptions, a vehicle generates in uplink 1995 bytes/s and 827 bytes/s for 10 and 2 CAMs/s, respectively. In order to simplify simulations, we assumed the same size for all CAMs, then, the CAM payload sizes are 200 and 414 bytes, for 10 and 2 CAMs/s, respectively. Moreover, IPv6 and UDP headers of 40 and 8 bytes, respectively, are added to each CAM packet.

For the downlink in the case of unicast, the ITS backend server, after receiving and processing uplink CAMs, sends to each vehicle a downlink CAM packet with the aggregation of all CAMs belonging to vehicles within the area of interest. It was assumed an area of interest of 362 m, which corresponds to the breaking distance computed for a reaction time of 1 s, a breaking deceleration of 4 m/s^2 (sand or concrete), and a velocity of 180 km/h.

In the case of eMBMS, CAMs are transmitted to all the vehicles inside the broadcasting area in which they were originated. In addition, the CAM updates from vehicles that are outside the broadcasting area but within 362 meters of the edge are also delivered inside the broadcasting area. For the shake of simplicity, it was assumed that every broadcasting area corresponds to the coverage area of one cell.

Finally, the use of header compression can be applied to reduce the size of headers of the user plane traffic over air interface. In the particular case of LTE, Robust Header Compression (RoHC) is supported for unicast transmissions but not for eMBMS transmissions. Based on some studies, it was assumed that an IPv6/UDP header of 48 bytes can be reduced to 3 bytes with the use of RoHC for unicast transmissions.

- RHW applications

In the RHW delivery scenario, the transmission of DENMs is event-triggered. This means that an event (e.g., an accident or mechanical failure) triggers the transmission of DENMs during a certain period of time in which the event is considered to be active. In this study, it was assumed that no more than one event can be active at any given moment of time within a certain area. The event-vehicle sends a DENM of 800 bytes to an ITS backend server which must deliver the message to all vehicles in the simulation scenario.

In the case of eMBMS, after receiving and processing the information, the ITS backend server sends the resulting DENM to the relevant eNBs by means of multicasting. Following this, each eNB broadcasts the DENM in downlink within its coverage area with a repetition period of 1 Hz or 10 Hz. In the case of unicast, the backend server sends the corresponding DENM in downlink to all the vehicles in the simulation scenario by means of p-t-p connections. Contrary to eMBMS, the DENM is not periodically repeated but rather transmitted only once to each vehicle using the TCP protocol. Again, the IPv6/TCP header of 60 bytes can be reduced to 4 bytes with the use of RoHC.

4.4 Simulation results

With all the assumptions presented in the previous section, a proper performance comparison between the unicast and eMBMS case was carried out to assess the delivery of vehicular safety services through LTE networks. This section presents the simulation results of both transmission modes. Firstly, the performance metrics used for unicast and eMBMS delivery simulations are presented in Section 4.4.1. Then, Section 4.4.2 shows the results of the analysis focused on the CA applications whereas the simulation results related to the of the RHW applications are presented in Section 4.4.3.

4.4.1 Performance metrics

In order to ensure a fair comparison of the results, specific performance metrics were used to process the simulation results. Next, the metrics used in both type of simulations are described.

The main goal of these simulations is to obtain the total amount of downlink resources needed to support each type of service in a LTE cell depending on the number of vehicles within the scenario. Based on this goal, we can also obtain the maximum number of vehicles that can be supported in the motorway scenario.

With the aim of computing the maximum number of vehicles that can be supported in the motorway scenario, vehicles must be classified as satisfied or not depending on their latency results. ETSI defines a maximum end-to-end delay of 100 ms. In this study only downlink simulations were carried out, then, we only obtained downlink latency results. In order to be more realistic, we added some additional delays to the downlink delay obtained by simulations. These additional delays correspond to:

- the uplink scheduling request: 6.5 ms,
- the processing at the source UE: 2 ms,
- the processing at the eNB of the source UE: 2 ms,
- the access to the ITS backend server: 5 ms,
- the processing at ITS backend server: 2 ms,

- the transmission to the eNB of the destination UE from the ITS backend server: 5 ms,
- the processing at the eNB of the destination UE: 2 ms,
- the processing at the destination UE: 2 ms.

In total, the additional delay is 26.5 ms. Therefore, a CAM transmitted to a vehicle is considered as delayed if the total packet delay is higher than 100 ms.

It is worth noting that the eMBMS simulations consist of a coverage study for the different MCS with single-cell eMBMS transmissions in order to obtain the maximum number of cars that can be supported within the motorway scenario. As other eMBMS simulations, the possible MCSs used for eMBMS transmissions in this study were those presented in Table A.3. The eMBMS coverage results for the LTE deployments of 5 and 10 km are shown in Figure 4.8.

The coverage level for a given MCS represents the percentage of users that are not in outage for this MCS. With the highest MCS that presents a coverage value greater than 95%, the maximum capacity that allows eMBMS can be obtained easily. This way, the maximum number of vehicles that can be supported by a cell will depend on this maximum capacity and the particular vehicular safety service configuration (i.e., service frequency, packet size,...). It is worth noting that the criterion of 95% is the same as defined in [94], nevertheless, more restrictive requirements, as for example 98%, can be used in

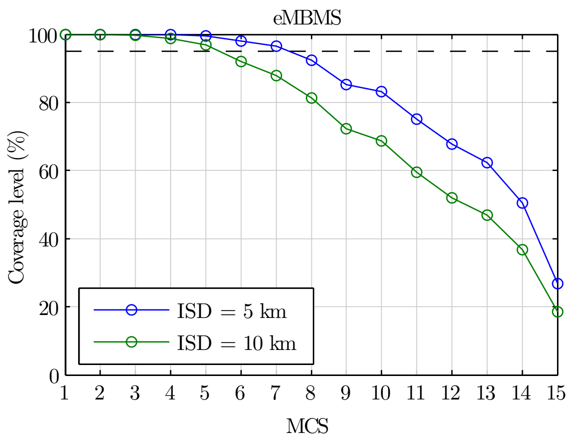

Figure 4.8: Coverage level vs. MCS for eMBMS transmissions with LTE deployments of 5 and 10 km of ISD in the motorway.

Table 4.4: Highest MCS for eMBMS transmissions with different coverage level requirements.

Coverage level requirement	**Highest MCS**	
	ISD 10 km	**ISD 5 km**
95% coverage	MCS 5	MCS 7
98% coverage	MCS 4	MCS 6

order to ensure the road safety service availability. Table 4.4 shows the highest MCS achieved for eMBMS in the motorway scenario with the two values of ISD, 5 and 10 km, and for the two coverage level requirements.

4.4.2 CA application analysis

Figure 4.9 shows the mean downlink resource usage depending on the number of vehicles within the motorway for the unicast and eMBMS delivery of CA applications. The upper part shows the results for an LTE deployment with an ISD of 10 km and the lower part shows the results with an ISD of 5 km. Although Table 4.4 shows different MCSs for the different ISDs, it was assumed the ones indicated for an ISD of 10 km –MCS 4 and MCS 5– for both deployments. In addition, it is worth remembering that the maximum resource usage for eMBMS is 60% of the channel capacity (6 subframes out of 10). For unicast, the LTE system adapts automatically the transmission mode to the current channel conditions of each user.

Results show that unicast outperforms eMBMS in terms of resource usage when the number of vehicles in the motorway is low. The reason for this is twofold. On the one hand, unicast transmissions benefit from link adaptation and advanced retransmissions mechanisms based on feedback information from receivers, which increase the spectral efficiency compared to broadcast transmissions. On the other hand, a low vehicle density entails a small number of downlink CAM packets to be delivered by the infrastructure. In unicast mode, each CAM packet transmitted by the vehicles in uplink has to be sent in downlink once to each vehicle within the area of interest. The higher the number of vehicles in the area, the higher the number of unicast transmissions that is needed and vice versa. In broadcast mode, downlink packets only needed to be sent once in the broadcast area regardless of the number of vehicles that are within the area of interest. As a result, eMBMS only starts outperforming the unicast mode when the number of vehicles in the motorway scenario increases above a certain value.

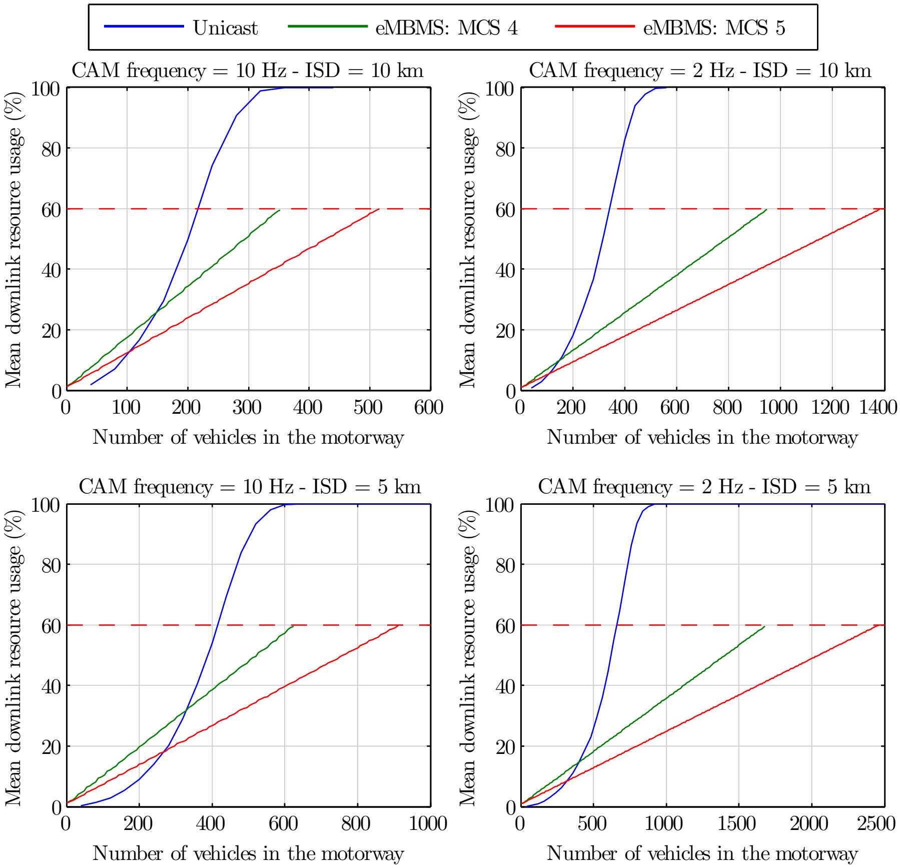

Figure 4.9: Downlink resource usage for unicast and eMBMS delivery of CA applications.

Figure 4.9 also shows that, for the same value of resource usage, the number of vehicles in the motorway for lower CAM transmission rates increases when comparing with higher ones. Moreover, for the same value of resource usage, the number of vehicles in the motorway for an ISD of 5 km increases when comparing with an ISD of 10 km. In this case, the maximum distance to the serving eNB is reduced, which entails that the useful signal received for a user is higher than for larger ISDs. As the motorway scenario is noise-limited, the SINR perceived by users is better for more dense deployments. Furthermore,

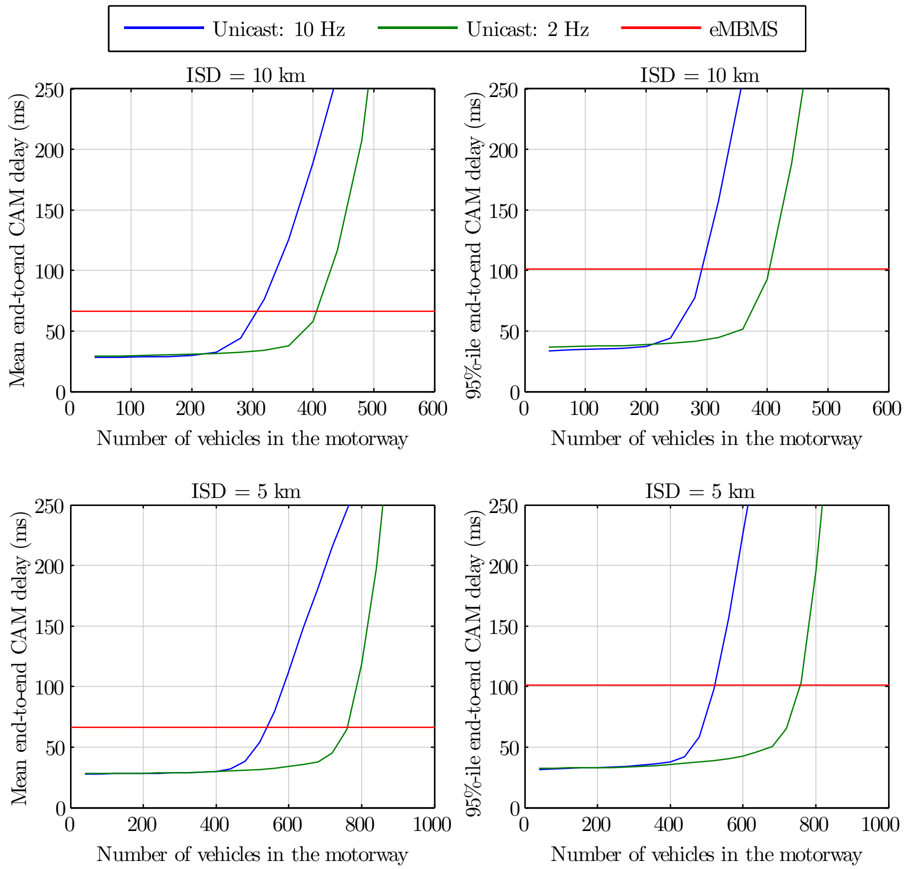

Figure 4.10: End-to-end delays for unicast and eMBMS delivery of CA applications.

the number of eNBs is doubled and, consequently, the number of supported users increases.

Figure 4.10 shows the end-to-end packet delay with an increasing number of vehicles in the motorway. The upper part shows the results for an LTE deployment with an ISD of 10 km and the lower part shows the results with an ISD of 5 km. Both average and 95% percentile are shown on the left and the right part, respectively. For eMBMS, it was assumed that the eNBs perform a dynamic eMBMS resource allocation using the lowest scheduling period, that is, 80 ms. Figure shows that the end-to-end delays in unicast mode are reasonable up to a certain number of vehicles in the scenario, where they begin to grow exponentially. Higher transmission frequencies of CAM reduce the number of vehicles that can be supported with acceptable delay. On the contrary, the highest latency of a CAM in the case of eMBMS delivery in downlink does not depend on the number of vehicles and is limited to 80 ms, which corresponds to the worse situation in which the message arrives at the beginning of the previous scheduling period. Then, the maximum end-to-end delay assumed for eMBMS is 106.5 ms (maximum downlink delay of 80 ms plus additional delays of 26.5).

Using the curves related to 95%-ile delays and assuming a maximum end-to-end CAM delay of 100 ms, we can obtain the maximum number of supported vehicles in the motorway scenario for each configuration with the unicast delivery mode. For an ISD of 10 km, the maximum numbers of vehicles in the motorway that fulfill the latency requirements are 291 and 403 for a CA service of 10 CAMs and 2 CAMs per second, respectively. For an ISD of 5 km, these values are increased up to 512 and 756 for a CA service of 10 CAMs and 2 CAMs per second, respectively. Table 4.5 compares the downlink resource usage of both delivery modes to support these maximum number of vehicles for each configuration. Results show the meaningful gain in terms of resource savings by using eMBMS for the delivery of CA applications. For a CAM transmission frequency of 10 Hz, the resource savings by using eMBMS instead of unicast are about 46% (MCS 4) and 63% (MCS 5). The resource savings are higher for a lower CAM transmission rate. Assuming 2 CAMs/s, the reduction is about 69% and 77% for the delivery of eMBMS using the MCS 4 and MCS 5, respectively.

The resource saving using eMBMS for the delivery of CA applications entails that the number of vehicles in the motorway that can be supported with eMBMS delivery is higher than the ones supported with unicast delivery. It is worth noting that the 95%-ile end-to-end delay for eMBMS is 101.18 ms, which is very close than the latency requirement established for these applications. Thus, we can assume that almost all CAMs delivered with eMBMS are received on-time. Table 4.6 summarizes the maximum number of vehicles that can be supported in the motorway by using eMBMS delivery. These values correspond to a total downlink resource usage of 60%.

It is worth noting that, for the eMBMS case, it may be possible that the maximum number of vehicles supported is limited by the uplink capacity. In simulations, we assumed two OFDM symbols per unicast subframe for PDCCH and one OFDM symbol per MBSFN subframe. With these control symbols, the maximum number of uplink grants per subframe is 7. With this maximum value, and assuming that there is enough uplink capacity to provide 7 different CAMs per subframe, the total number of CAMs transmitted in each cell located

Table 4.5: Downlink resource usage for unicast and eMBMS delivery for the maximum number of vehicles supported by unicast.

ISD	CAM frequency	Number of vehicles	Downlink resource usage (%)		
			Unicast	eMBMS: MCS 4	eMBMS: MCS 5
10 km	10 Hz	291	92.95	49.46	34.2
	2 Hz	403	83.57	25.77	18
5 km	10 Hz	521	93.53	49.72	34.5
	2 Hz	756	85	27.21	19.03

Table 4.6: Maximum number of vehicles in the motorway for the eMBMS delivery of CA applications.

ISD	CAM frequency	Number of vehicles	
		eMBMS: MCS 4	eMBMS: MCS 5
10 km	10 Hz	352	516
	2 Hz	948	1384
5 km	10 Hz	624	912
	2 Hz	1680	2456

at the motorway with a CAM transmission frequency of 10 Hz is 700, whereas it increases up to 3500 per cell with a CAM transmission frequency of 2 Hz. If these values are multiplied by the number of cells in each type of deployment, we can conclude that capacity is not limited by the uplink. In a more conservative case, for example 3 CAMs per subframe, the total number of CAMs per cell are 300 and 1500 for a CAM transmission frequency of 10 and 2 Hz, respectively. Again, the capacity for the CA service is limited by the downlink capacity.

4.4.3 RHW application analysis

Figure 4.11 shows the mean downlink resource usage depending on the number of vehicles within the motorway for the unicast and eMBMS delivery of DENMs with an ISD of 10 km. These simulations consist of snapshots of 2 seconds

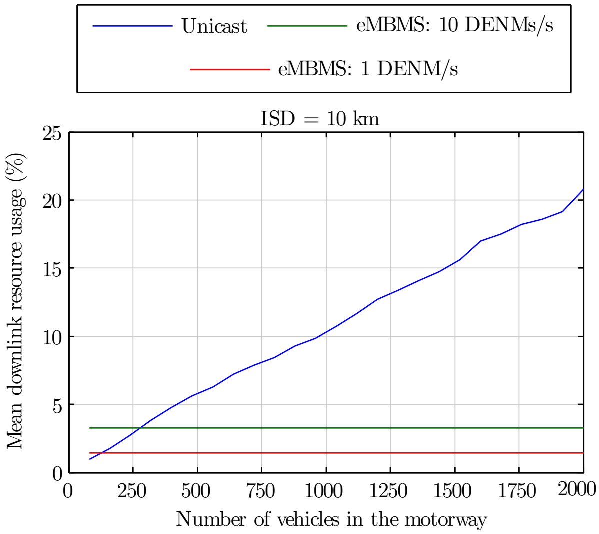

Figure 4.11: Downlink resource usage for unicast and eMBMS delivery of RHW applications.

where a DENM is triggered. For eMBMS, it was assumed the MCSs 4 and two different DENM transmission rates: 1 DENM/s and 10 DENM/s.

Results show that the resource consumption with unicast delivery increases with higher number of vehicles in the motorway whereas it does not depend on the motorway load using eMBMS delivery. With a broadcast transmission rate of 1 DENM/s and 10 DENM/s, the downlink resource usage in these 2 seconds is 1.45 and 3.25%. For few users per cell, unicast delivery outperforms eMBMS delivery, whereas eMBMS is already better than unicast from around 128 and 276 users in the motorway with a broadcast transmission rate of 1 DENM/s and 10 DENM/s, respectively.

These results show that the capacity required when delivering RHW applications is much lower than in the case of CA applications. Furthermore, the gain of eMBMS in terms of resource savings compared to the unicast mode is much higher than in the CA case, which is explained by the localized nature of CA applications as opposed to the broadcast nature of RHW applications (the same message is delivered to all the vehicles in a wide area).

Concerning delay results, Figure 4.12 shows the end-to-end packet delays of DENMs depending on the number of vehicles in the motorway for both de-

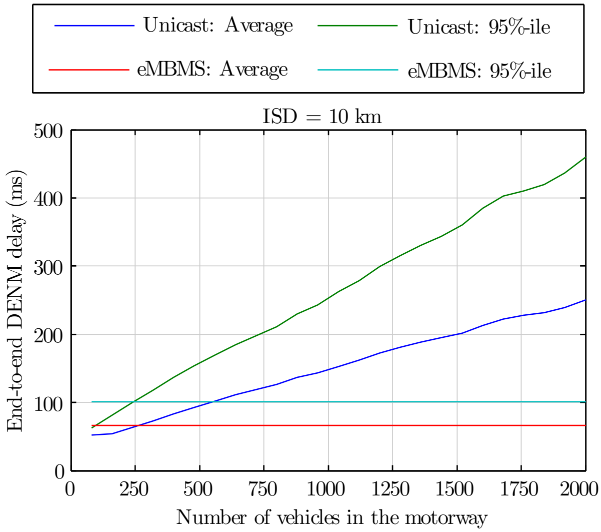

Figure 4.12: End-to-end delays for unicast and eMBMS delivery of RHW applications.

livery modes with an ISD of 10 km. It shows both mean and 95%-ile delays. This figure also illustrates that the end-to-end delay with unicast delivery increases with the number of vehicles in the motorway area, whereas it does not depend on the cell load using eMBMS delivery mode. For eMBMS, the delay depends on the arrival of the DENM packet at the eNB with respect to the beginning of the MSP. Similar to the figure of downlink resources, unicast delivery outperforms eMBMS delivery for few users in the motorway, whereas eMBMS is already better than unicast from around 243 users considering the 95%-ile delay curves.

4.5 Cost analysis

One of the objectives of this chapter is to demonstrate the advantages of broadcasting technologies for the provision of vehicular safety applications in LTE networks not only in terms of resource utilizations and latency but also in terms of delivery costs. To this end, a cost modeling calculation must be first defined, followed by a fair comparison of costs. For the sake of simplicity, only the cost in downlink for the CA use case is analyzed.

Table 4.7: Assumptions for the cost analysis of the vehicular safety services delivery.

Concept	Value
Life expectancy of a vehicle	9 years
Vehicle use per day	79 min
MNO income per MB	0.01 €
MNO sustained throughput/cell	17.3 Mbps
MNO income/cell in vehicle use period	97.75 €
Mean number of vehicle per cell	60

4.5.1 Cost modeling and assumptions

The state of the art in Europe for pay per use ranges from 0.05 €/MB down to 0.01 €/MB. With these considerations in mind, a model including a fare of 0.01 €/MB was assumed. Other assumptions concerning the cost analysis are summarized in Table 4.7. Regarding the modeling of the costs, it was firstly assumed a win-win situation in which all the stakeholders, that is, the MNOs, governments, citizens and the car manufacturers, are satisfied. These assumptions are the following:

- From the governments' point of view, ITS applications improve the road safety, reduce accidents and lower the costs in terms of rescues and medical care. Therefore, ITS capabilities were assumed to be enforced by governments in all the cars and MNOs in order to guarantee the coverage, prioritization and inter-operability of the service.

- From the citizens' point of view, it is unforeseeable that users would be willing to pay for the additional cost derived from the data exchange in ITS applications. Provided the enforcement from governments, users are not charged by this service directly, although the final cost of cars could be increased by car manufacturers in order to compensate for the extra cost.

- From the automotive industry point of view, ITS capabilities have to be incorporated in the majority of the cars in order to enable ITS applications. Together with the operators, the automotive industry will pay for the ITS deployment and the cost of the data traffic exchange. In compensation, car manufacturers may increase the price of cars in order to encompass part of the costs incurred by the new service.

- From the MNOs point of view, it is necessary to adapt the network in order to support ITS applications. This requires modifying algorithms via software updates and including new servers and gateways among different operators. Moreover, the provision of ITS applications with eMBMS entails a certain loss of resources to other conventional users. In order to identify a win-win scenario, the cost modelling shall find the situation in which the benefits derived from eMBMS overcomes the loss of revenue derived from the loss of unicast resources.

4.5.2 Cost for CA applications

Figure 4.13 shows the cost per vehicle and day derived from the delivery of CA application messages with a CAM transmission frequency of 10 and 2 Hz. The left part shows the cost results for an ISD of 10 km whereas the right part shows the results for an ISD of 5 km. For this calculation, we have previously obtained the maximum traffic carried by the LTE network in the real motorway scenario deployment assuming full resource usage. Using the income per MB, we derive the total income of the MNO per resource unit. Then, using simulations, we calculate the required amount of resources to deliver CA messages for a certain number of vehicles and, therefore, the cost per vehicle and day, after normalizing by the mean vehicle usage per day. For eMBMS, it was used the resource usage results with the MCS 4. It is worth noting that the curves for

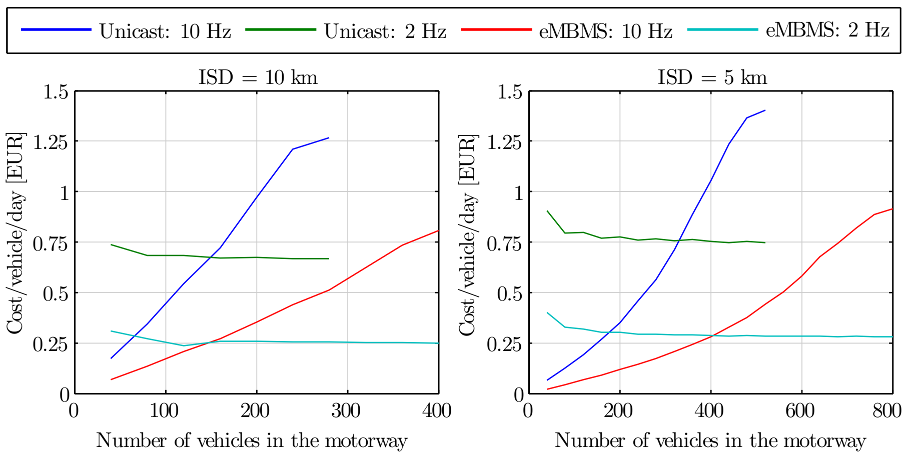

Figure 4.13: Cost per vehicle and day for CA applications.

Table 4.8: Price increase per vehicle comparing unicast and eMBMS delivery for different frequencies in the CAM transmission.

ISD	CAM transmission frequency	Unicast delivery cost (€)	eMBMS delivery cost (€)
10 km	10 Hz	4161,60	2197,85
	2 Hz	2656,38	821,75
5 km	10 Hz	4614,77	2453,37
	2 Hz	2908,69	924,16

each configuration are limited to the maximum number of vehicles supported by unicast delivery (see Table 4.5).

Results show that, in the case of unicast, the cost per vehicle increases with the number of vehicles in the motorway due to the higher utilization of radio resources. For eMBMS, the cost actually decreases with the number of vehicles, and broadcasting transmissions become more profitable when the number of active vehicles increases beyond a certain value. Thus, the larger the number of vehicles, the higher the gain in terms of cost reduction by using eMBMS.

Finally, Table 4.8 summarizes the increase in the cost per vehicle caused by the transmission of CAMs in CA applications for these maximum number of vehicles in the motorway concerning unicast delivery. This calculation is made taking into account an average life expectancy of a car of 9 years. Note that, in the case of eMBMS, the cost per vehicle is significantly lower than the cost per vehicle with unicast and this reduction is larger with lower CAM transmission rates. The cost per vehicle is reduced a 47% and a 60% with eMBMS for a CAM transmission frequency of 10 and 2 Hz.

4.6 Conclusions

This chapter has analyzed the provision of vehicular safety services over LTE cellular networks comparing both unicast and broadcast delivery modes in terms of capacity, latency and cost. The capacity and latency comparison of both transmission modes has been performed through several system-level simulations whereas the cost comparison has been performed through a cost modeling analysis.

The results presented in this chapter have demonstrated the interest on the use of broadcast technologies for the provision of vehicular safety services based on Cooperative Awareness (CA) and Road Hazard Warning (RHW) applications. The results in terms of resource consumption and cost modeling support the conclusion that eMBMS is much more efficient than the unicast delivery mode when the number of vehicles on the road is high.

Concerning the downlink resource usage, results have shown the capacity required when delivering CA applications is much higher than in the case of RHW applications. Using the unicast deliver for CAMs, the maximum system capacity is achieved for a low density of vehicles in the motorway. High density of vehicles in the motorway only can be supported by using eMBMS and if the CAM transmission rate is reduced.

This chapter has also discussed a possible configuration of the LTE network for the delivery of vehicular safety applications with eMBMS. In particular, a solution based on a continuous eMBMS service for road safety services together with a dynamic allocation of eMBMS resources has been proposed for latency and network efficiency reasons. Concerning the architecture, we have analyzed the impact of the ITS backend server and the possibility to merge it with the BM-SC for the feasibility of multi-operator scenarios.

Chapter 5

Evolution of mobile broadcasting towards 5G

One of the key challenges for MNOs is to cope with the increase of mobile video traffic expected for the coming years. Moreover, the consumption of video content over mobile networks, which is a mix of linear TV and on-demand video services, represents a challenge that requires a combined broadcast/unicast delivery model.

Mobile industry has adopted LTE and its evolution LTE-A as worldwide 4G cellular technologies and MNOs expect to cope with the increasing demand of mobile video data by combining LTE/LTE-A unicast transmissions with eMBMS. However, the current spectrum allocations for mobile broadband systems may be a big handicap for MNOs to address this mobile traffic demand growth.

In 2020, the envisaged spectrum requirements for mobile broadband range between 1280 MHz and 1720 MHz [15]. However, the current spectrum allocated by ITU is much lower than these values in the three ITU Regions. The last decisions of the ITU regarding spectrum reallocations focus on reducing this deficit. In particular, ITU decided in the WRC-07 to allocate part of the UHF band traditionally used for analogue TV broadcasting to IMT technologies. This band, also known as digital dividend [16], ranges from 790 to 862 MHz in Region 1, and from 698 to 790 MHz in Region 2 and Region 3, and requires additional guard bands to avoid interferences between cellular and broadcast technologies. Moreover, the worldwide allocation of the 700 MHz band to IMT technologies is on the agenda for the next WRC-15 [15].

For broadcasters, releasing frequencies for mobile services in many countries where the DTT services have an important penetration will require a costly retune of networks and receiver infrastructures. At the same time, despite broadcast industry can improve the capacity of DTT networks with the introduction of new generation broadcast standards, the access to sufficient UHF spectrum is still essential in maintaining existing DTT networks and enabling service to smartphones and tablets.

The scenario in this framework would end up with two complete different industries, with different network infrastructures and business models competing for market and spectrum. However, in order to solve the problem in broadcasting spectrum, several proposals for cooperation between mobile broadband and broadcast industries have emerged in recent years [17, 18]. The main goal of these proposals is to allow the transmission of mass multimedia services to mobile and stationary receivers through the different network infrastructures used by both industries.

This chapter reviews these proposals for the cooperation between both industries and proposes a different approach by which the definition of the future 5G mobile broadband communication system could bring together the cellular and broadcast industries to form a single fixed and mobile converged network. The rest of the chapter is organized as follows. Section 5.1 presents the state of the art on the evolution of mobile and broadcast technologies. The first approaches for the cooperation between mobile broadband and broadcast are described in Section 5.2. They are the starting point for the definition of a joint solution within 5G. Section 5.3 discusses the challenges of the definition of such a converged solution. Finally, some conclusion remarks are given in Section 5.4.

5.1 Evolution of mobile communications and terrestrial broadcasting standards

Figure 5.1 shows the mobile communications and DTT standards landscape. On the one hand, mobile industry evolves towards the future 5G mobile broadband communications, whereas broadcast industry evolves towards a global DTT standard.

5.1.1 Mobile industry: evolution towards the future 5G system

From the Second Generation (2G) of mobile cellular networks, the mobile communications sector has seen many competing radio standards mainly developed by the 3GPP, the Third Generation Partnership Project 2 (3GPP2) and the

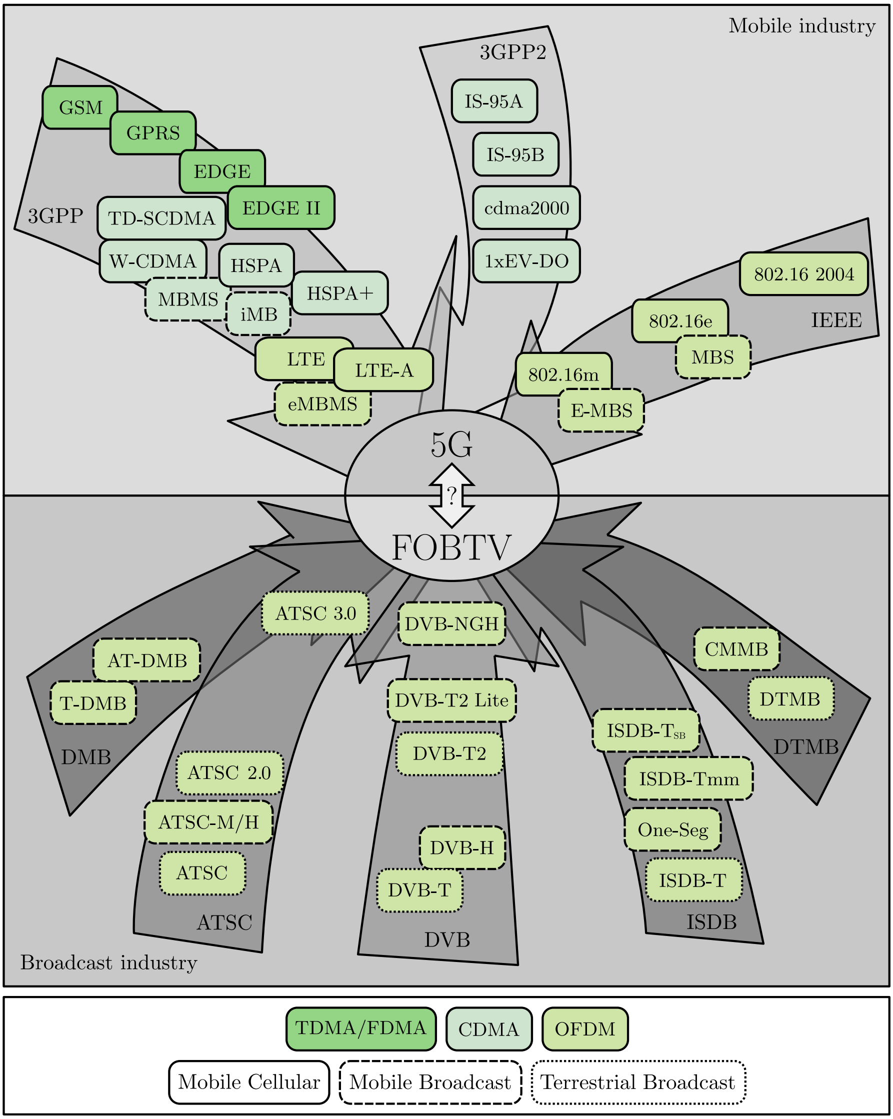

Figure 5.1: Mobile communications and DTT standards landscape.

IEEE. However, the dynamics of 4G is changing this landscape since all existing mobile cellular systems are converging towards a single technology, that is, the 3GPP LTE.

LTE was designed from the beginning with the goal of evolving the radio access technologies under the assumption that all services would be packet-switched. Unlike previous technologies, LTE adopted OFDM as its radio access technology, which is the one dominating the latest evolutions of all mobile radio standards. This change was accompanied by an evolution of the non-radio aspects of the complete system towards a flat and all-IP system architecture. It is worth noting that the latest cellular generation developed by the IEEE, known as 802.16m, has similar targets to the evolution of LTE, that is, LTE-A. However, the IEEE 802.16 family has not been designed with the same emphasis on mobility and compatibility with operators' core networks as the 3GPP technology family.

Concerning the state of the art on 4G network deployments, the number of commercial LTE networks and handsets is increasing very rapidly worldwide. By the end of 2014, 360 LTE networks have commercially been launched worldwide and this number is expected to reach around 450 networks by end 2015 [96]. This worldwide adoption gives to eMBMS the edge over all its mobile broadcast competitors to provide mass multimedia services to mobile devices. eMBMS, also known commercially as LTE Broadcast, represents a new profitable business proposition for MNOs through service differentiation, new revenue opportunities, and more efficient distribution of live video services and other digital media. The end-to-end IP architecture enables the coexistence of unicast and broadcast services with high capacity, high bandwidth and high scalability. Moreover, the deployment costs are significantly lower than other broadcast alternatives due to its easy integration with LTE infrastructure and mobile device chipsets.

Concerning LTE Broadcast, mobile users have seen some milestones related to eMBMS deployments in 2014 [96]. Several MNOs have already deployed their eMBMS networks completing successfully the first trials by the end of January 2014. As some examples, Verizon Wireless used the Super Bowl in New York as a test case for the LTE Broadcast technology and the Australian operator Telstra completed a live demonstration of LTE Broadcast solution in a stadium environment during a cricket match in Melbourne. In addition, Korea Telecom completed the world's first commercial launch of LTE Broadcast services using eMBMS technology by the end of Juanuary 2014. Later on, Vodafone Germany and KPN made the Europe's first trials of LTE Broadcast in a football stadium in February and May 2014, respectively. Table 5.1 summarizes the different LTE Broadcast trials and commercial deployments carried out recently [6].

Table 5.1: LTE Broadcast market developments.

Operator, content owner	**Activity**
China Mobile (China)	Public demonstration with LTE TDD at MWC (February 2013)
Smart (Philippines)	Trialled using 2.1 GHz spectrum (November 2013)
Verizon Wireless (USA)	Trialled during SuperBowl (Janurary 2014). Commercial service targeted for 2015
Telstra (Australia)	World's first stadium trial during a cricket match (January 2014)
KT (South Korea)	World's first commercial launch (January 2014)
Vodafone (Germany)	Europe's first stadium trial at a soccer match (February 2014)
KPN (Netherlands)	Trialled during a soccer match (May 2014)
Orange (France)	Trialled during French Tennis Open 2014 (May 2014)
China Telecom (China)	Trialled in Nanjing (June 2014). Pre-commercial use for Summer Youth Olympic Games (August 2014)
EE/BBC (UK)	Trialled during Commonwealth Games (July 2014)
Polkomtel (Poland)	Trialled at a volleyball match in Warsaw (August 2014)
Globe (Philippines)	Showcased eMBMS during a forum (August 2014). Targeting commercial launch in 2015
Three UK (UK)	Trialled over its LTE network in Maidenhead
AT&T (USA)	Trialled and commercial service targeted for 2015
RJIL (India)	Trialled in Mumbai
IFR (Germany)	Trialling in Munich using 700 MHz spectrum
Meo (Portugal)	Trialling
SingTel (Singapore)	Trialling
Etisalat (UAE)	Trialling

However, although MNOs are currently investing on 4G network deployments, the mobile industry is already working on the definition of the future 5G mobile communication system. The three main requirements for 5G wireless networks are [97]: to support massive capacity and connectivity; to carry a diverse set of services, applications and users with extremely diverging requirements; and to make a flexible and efficient use of the available spectrum, whether contiguous or not, supporting wildly different network deployment scenarios. Moreover, following the current requirements and expectations from both users and operators, it is expected that the future 5G wireless networks also include the efficient provision of mass mobile multimedia services through one or several broadcast transmission modes.

5.1.2 Broadcasters: evolution towards a global terrestrial standard

The need for replacing analogue TV to make a more efficient use of the broadcast radio spectrum and to improve the quality of TV services motivated the development of DTT systems [98]. There are five digital TV standardization organizations in the world: Advanced Television Systems Committee (ATSC) in North America, Digital Video Broadcasting Project (DVB) in Europe, Digital Terrestrial Multimedia Broadcast (DTMB) in China, Integrated Services Digital Broadcasting (ISDB) in Japan and Digital Multimedia Broadcasting (DMB) in Korea.

DVB standards are the most adopted worldwide being currently two of these standards, DVB-T2 and DVB-NGH, the most advanced DTT systems for fixed and mobile devices, respectively. DVB-T2 provides at least 50% capacity increase over the other existing standards and its evolution to handhelds, DVB-NGH, includes the use of multiple antennas at transmitter and receiver side and other enhancements with respect to DVB-T2.

Despite the fact that DVB-NGH outperforms previous DTT systems to support large-scale consumption of mass multimedia services in mobile devices, there are no plans for its commercial deployment. So far, in many countries mobile TV services either did not reach the market or were launched and promptly stopped. The only successful stories among the mobile broadcasting systems are One-Seg in Japan and Terrestrial - Digital Multimedia Broadcasting (T-DMB) in South Korea. However, in these two cases, the transmission of mobile broadcasting services was requested by the national regulators.

The high fragmentation of the DTT market and the need for taking benefit from the economies of scale have recently motivated the approaches and wishes of cooperation among the different broadcasting organizations. The Future of Broadcast Television (FOBTV) initiative was launched in 2012 with the aim of creating a common working scenario for the future generation of broadcast terrestrial systems to avoid competing standards, overlap, and inefficient deployment of new services. In particular, the goals of the FOBTV initiative include [99]:

- Developing future ecosystem models for terrestrial broadcasting taking into account business, regulatory, and technical environments.
- Developing requirements for next-generation terrestrial broadcast systems.
- Fostering collaboration of digital TV development laboratories.
- Recommending major technologies to be used as the basis for new standards.
- Requesting standardization of selected technologies (layers) by appropriate standards of development organizations.

Thus, the initiatives for a unified terrestrial broadcast standards targeting both fixed and mobile reception could favor economies of scale thus motivating its implementation on mobile devices.

The latest milestone in the development of the next-generation digital broadcast technologies is the Advanced Television Systems Committee 3.0 (ATSC 3.0) standard, which will replace the current systems used in the United States of America (USA) and aims at being a global standard. Figure 5.2 shows the development timeline of ATSC 3.0 [100], which involves not only the physical layer, but also the management and protocols, and applications and presentation layers. In September 2013, eleven detailed physical layer proposals were received [101], taking many of these technical proposals the DVB-T2 and/or DVB-NGH standards as baseline. Therefore, it is likely that the upcoming physical layer of the ATSC 3.0 had significant similarities with the last DVB standards. In that case, the world could take full advantage of global economies of scale.

5.2 First attempts for the mobile broadband-broadcast cooperation

As commented in previous chapters, eMBMS is currently only supported in a mixed carrier mode, where broadcast and unicast data share the carrier capacity. In particular, up to 60% of the total LTE resources can be reserved for eMBMS. The eMBMS subframes use OFDM symbols with a longer CP of

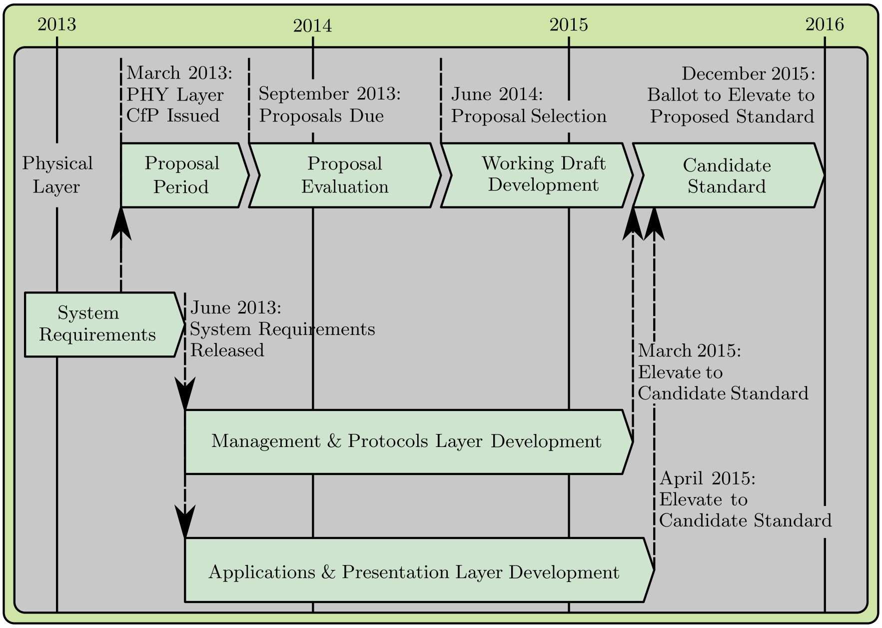

Figure 5.2: ATSC 3.0 standard development timeline.

16.67 μs, which allows the construction of SFNs between multiple cells with a maximum of 5 km ISD. Moreover, it is possible to double the CP length to 33.33 μs (10 km SFN distance) for MBSFN with dedicated carrier deployments. Although the physical layer features of MBSFN dedicated carrier are already defined, it is not supported in current releases of LTE and LTE-A.

From the broadcasters' point of view, current eMBMS features do not address all mobile broadcast use cases, since its low delay spread tolerance entails that eMBMS can be only deployed on dense Low Power Low Tower (LPLT) networks. Traditional broadcast networks are more efficient for broadcasting TV services to a large number of subscribers due their High Power High Tower (HPHT) networks, which cover large areas. Typical SFN distances used in traditional broadcast networks range between 50 and 90 km. To cover these large distances, DTT systems use long cyclic prefix as for example 224 μs and 448 μs in DVB-T2.

On the one hand, one of the challenges of eMBMS is its deployment in HPHT networks. This topic was analyzed in [102] concluding that eMBMS current standard is not suitable for HPHT networks. Results show that the effect is meaningfully worse since eMBMS, with the current configuration, cannot provide a similar coverage as DTT systems like DVB-T2 when using the same HPHT network topology. On the other hand, the HPHT networks used by broadcasters are designed for fixed reception and broadcasters need more infrastructure in order to cope with mobile reception.

The optimum solution would be a combination of existing infrastructure of both broadcasters and MNOs to address both fixed and mobile reception in an efficient manner. This section gives an overview about possible ways of complementing wireless broadband systems using terrestrial broadcast HPHT networks.

5.2.1 Technical approaches for 3GPP and DVB cooperation

In November 2010, the DVB forum contacted 3GPP to consider a potential collaboration in the area of mobile broadcasting. A joint workshop took place in March 2011 with presentations from 3GPP and DVB standardization activities and, two months later, the creation of a study item was proposed to the 3GPP [103]. This proposal introduced the concept of CBS to be used in a 3GPP mobile communications and DVB-based broadcasting network.

Although this proposal was not accepted by 3GPP due to lack of support from MNOs, broadcast industry and academia continued working on 3GPP and DVB cooperation and several technical approaches have been recently proposed. The main assumption is the evolution of the broadcast capability of current 3GPP eMBMS in terms of capacity, coverage and quality of service to match traditional broadcast networks.

This section describes two different approaches for 3GPP and DVB cooperation. Both approaches use the FEF concept defined in DVB-T2 system, which is described firstly. One of the approaches has been provided by the French Mobile Multi-Media (M^3) project and consists of the definition of a Common Physical Layer (CPHY) based on the convergence of eMBMS and DVB-NGH. The other one, known as the "Tower overlay over LTE-A", has been proposed by the Institut für Nachrichtentechnik of the Technische Universität Braunschweig, Germany.

5.2.1.1 Future extension frames in DVB-T2

- FEF concept

Figure 5.3 shows the physical frame structure of DVB-T2, which consists of super frames, frames, and OFDM symbols. Super frames comprise an integer number of frames that may be of two types: T2 frames and FEFs. Likewise,

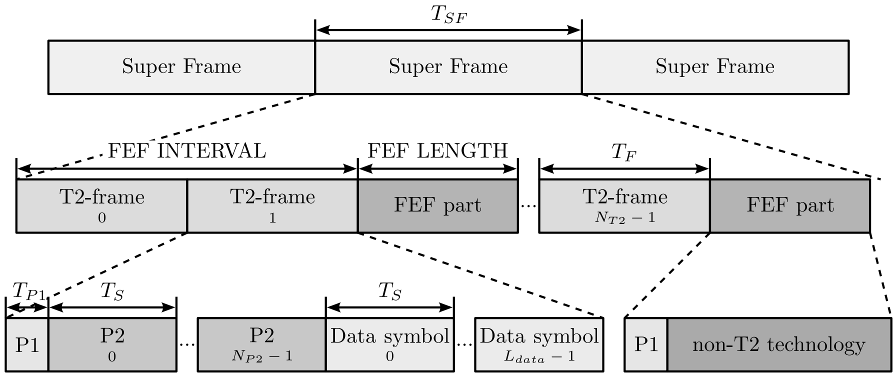

Figure 5.3: The DVB-T2 frame structure, showing the division into super frames, T2-frames and FEF.

each frame is formed by an integer number of OFDM symbols, either preamble symbols, which carry control information, or data symbols.

P1 and P2 are the preambles that provide control information to DVB-T2 receivers. P1 is the first OFDM symbol of each T2 frame and FEF part, and consists of a 1K OFDM symbol used for fast synchronization. It also carries some basic transmission parameters, like the frame type (e.g., T2, mobile profile of T2 known as T2-Lite, or handheld evolution of T2 known as DVB-NGH). In T2 frames, one or several P2 symbols, depending on the Fast Fourier Transform (FFT) size, are inserted after the P1 symbol. These preamble symbols have the same FFT size as data symbols and convey the rest of Layer 1 (L1) signaling information. This signaling enables the reception of subsequent data symbols that contain the current DVB-T2 services.

L1 signaling configures the number of T2 frames and FEF parts carried by a super frame. The minimum and maximum numbers of T2 frames in a super frame are 2 and 255, respectively, being all of them of the same duration. The maximum length of a T2 frame, T_F, is 250 ms. The use of FEFs is optional, but if included in the transmission, super frames must start with a T2 frame and end with a FEFs. The pattern insertion scheme of FEFs can be configured on a super frame basis. The maximum number of FEFs in a super frame is 255, that is, one FEFs after every T2 frame. As an example, Figure 5.3 illustrates a frame structure in which there is one FEF every two T2 frames.

FEFs allow combining in the same frequency legacy DVB-T2 transmissions with other technologies. They can be inserted between T2 frames to enable a flexible mix of services within a single multiplex in a time division manner. During FEFs, DVB-T2 receivers ignore the received signal in such a way that any service can be inserted in these temporary slots without affecting the DVB-T2 reception. The only attributes of FEFs defined in the standard are the following:

- They shall begin with a preamble P1 symbol.
- Their position and duration in the super frame are indicated in the L1 signaling within the T2 frames.

The maximum length of a FEF part is 250 ms for the T2-base profile, whereas for T2-Lite and DVB-NGH it has been extended up to 1 s [104]. The existing DVB-T2 receivers are not expected to decode FEFs. They simply must be able to detect and correctly handle FEF parts so that the reception of T2 frames is not disturbed.

Although FEFs were designed to enable future extensions of the DVB-T2 standard, other use cases are possible. As depicted in Figure 5.3, data from another technology can be transmitted in the DVB-T2 spectrum taking advantage of the temporal multiplexing of services that enable the FEF concept. It is worth noting that the T2 system is always responsible for inserting the P1 symbol at the beginning of all FEF parts so that all T2 receivers can detect the FEFs parts correctly.

- L1 Signalling related to FEF

The use of FEFs is signaled in the preamble P1 and P2 symbols. The P1 symbol has two signaling fields S1 and S2, with three and four signaling bits, respectively. The S1 field is used to distinguish the preamble format and, hence, the frame type. The frame type can be either T2 or a FEF. This FEF can be used for T2-Lite, DVB-NGH or non-T2 applications. Currently, there are several types of FEFs defined fot T2-Lite and DVB-NGH and there is one combination devoted for non-T2 applications –with S1 field equal to 010–. This case can be used to time-multiplex other services like LTE/LTE-A.

For DVB-T2, T2-Lite, and DVB-NGH, the S2 field mainly indicates the FFT size, but it has one bit dedicated to the FEFs. This bit specifies whether the preambles are all of the same type or not, that is, if more than one type of frame exists in the super frame. This speeds up the scanning process.

L1 signaling data in the preamble P2 provides, among others, the guard interval, the number of T2 frames per super frame, N_{T2}, the number of data symbols, L_{DATA}, the type of the associated FEF part, FEF_ TYPE, the length of the associated FEF part, FEF_ LENGTH, and the number of T2-frames between two FEF parts, FEF_ INTERVAL. It should be pointed out that the

FEF_ LENGTH indicates the length of the FEF parts in elementary time periods[1], T, from the start of the P1 symbol of the FEF part to the start of the P1 symbol of the next T2 frame.

Therefore, with N_{T2} and FEF_ INTERVAL the receiver can compute the number of FEFs in a super frame, N_{FEF}, and subsequently the total super frame duration, T_{SF}.

5.2.1.2 3GPP eMBMS/DVB-NGH physical layer convergence

The French M^3 project evaluated and analyzed convergence possibilities of the CPHY providing broadcast capabilities to the 3GPP LTE and DVB-NGH systems [105]. The proposed CPHY specifications are devised to act as an enabler for the deployment of broadcasting transmission modes over various network infrastructures, whether it be conventional terrestrial broadcast, broadcast networks or even satellites ones. In order to define such CPHY specifications, several challenges were identified [17]:

- The CPHY waveform should be sufficiently scalable to be fully compatible with the radio deployment planning of the targeted networks in terms of frequency bands, coverage areas and frequency planning strategies. Concerning frequency bands, the CPHY has to be able to address at once typical frequency bands for mobile communications and digital TV. Regarding coverage areas, the CPHY waveform has to be shaped in order to ensure the coverage of cells whose sizes ranges from a few hundred meters to several tens of kilometers.

- The CPHY should take advantage of the full downlink feature of broadcast transmissions by defining long frame durations. Using long frames allows the constellations and coding rates to be optimized for large codeword lengths, making the system perform closer to the Shannon limit. For mobile reception scenarios with time-variant channels, interleaving schemes should be also applied over a large time spread to take advantage of time diversity.

- The CPHY specifications should be based on a framing structure adapted to p-t-m transmissions. Such transmissions ensure a universal coverage, which entails that a given user should be able to access the broadcast contents at every time without engaging complex high-level process such as session control protocols.

[1] Samples in the receiver

Considering these challenges and after analyzing both eMBMS and last DVB standards –DVB-T2 and DVB-NGH–, they proposed a unified physical layer for mobile broadcasting scenarios with the different advantages of both system designs. This approach involves starting from LTE eMBMS specifications and making them evolve to integrate broadcasters' requirements in the perspective of a deployment of the CPHY over traditional broadcasting infrastructures, terrestrial and satellite.

To this end, they proposed the modification of eMBMS specifications according to the following steps:

1) Define a frame structure compatible with the DVB framing.

2) Modify the OFDM parameters in order to address typical broadcasters' bandwidths.

3) Increase the OFDM guard interval duration for SFN operation at the scale of typical broadcasters' cells.

4) Increase time diversity exploitation with time interleaving.

5) Design appropriate pilot patterns according to the previous modifications.

More specifically, CPHY was initially assumed to be transmitted on a dedicated carrier either by MNOs, using mobile cellular networks, or broadcasters using HPHT networks. However, CPHY could be also transmitted in-band with LTE/LTE-A unicast, as it is the case in the current eMBMS specifications, or in-band with DVB-T2 broadcast, by using the FEF concept described before.

The CPHY should also be compatible with the typical bandwidth values of both standards: 6, 7 and 8 MHz from DVB-T2, and 5 and 10 MHz from LTE. Moreover, in order to enlarge the coverage area of CPHY with respect to current eMBMS standard, it was proposed the use of physical layer configurations with longer CPs. The use of longer CPs is combined with lower subcarrier spacings and higher FFT sizes, which improves the coverage area but also reduces the maximum Doppler frequency. Table 5.2 summarizes the maximum Doppler frequency and ISD obtained for 600 MHz, when dividing the current eMBMS subcarrier spacing values –the two first rows in the table– by factors of 2, 3 and 6, respectively. It is worth noting that an acceptable maximum speed of 225 km/h can be supported with the lowest subcarrier spacing value, that is, 1.25 kHz.

Along with these eMBMS enhancements, this approach proposes the use of time interleaving schemes at the physical layer based on enlarged transmission time interval and time slicing concept so as to exploit time diversity.

Table 5.2: CPHY parameters for coverage area extension in the UHF band (bandwidth: 8 MHz, central frequency: 600 MHz).

Subcarrier spacing (kHz)	FFT size	CP length (μs)	OFDM symbols per subframe	Coverage radius (km)	Maximum Doppler shift (Hz)
15	1024	16.67	12	5	1500
7.5	2048	33.33	6	10	750
3.75	2048	66.67	3	20	375
2.5	3072	100	2	30	250
1.25	6144	200	1	60	125

5.2.1.3 Tower overlay over LTE-Advanced

The other proposal for 3GPP and DVB cooperation, known as “Tower overlay over LTE-A” [18, 106] is based on the FEF concept together with the LTE-A carrier aggregation concept.

- Carrier aggregation

Carrier aggregation is one of the key features of LTE-A Release 10 [107] to fulfill the IMT-Advanced requirement of 1 Gbps peak data rate for low-mobility user. This feature allows for the use of a maximum bandwidth of 100 MHz by means of the aggregation of up to 5 legacy LTE carriers of 20 MHz. As Figure 5.4 shows, carrier aggregation is designed to support aggregation of a variety of different arrangements of carriers, including carriers of the same or different bandwidths, adjacent or non-adjacent carriers in the same frequency band, and carriers in different frequency bands.

All carriers in LTE-A Release 10 are designed to be backward-compatible. This means that each carrier is fully accessible to legacy LTE UEs. Therefore, essential Release 8 channels and signals such as synchronization signals and system information are transmitted on each carrier. Moreover, each carrier appears as a separate cell with its own Cell ID. A UE that is configured for carrier aggregation is connected to one primary cell and up to four secondary cells. Firstly, the UE establishes the radio access connection with a serving cell that becomes the primary cell. This primary cell plays an essential role with respect to security, mobility information and connection maintenance. Secondary cells may be configured after connection establishment, just to provide additional

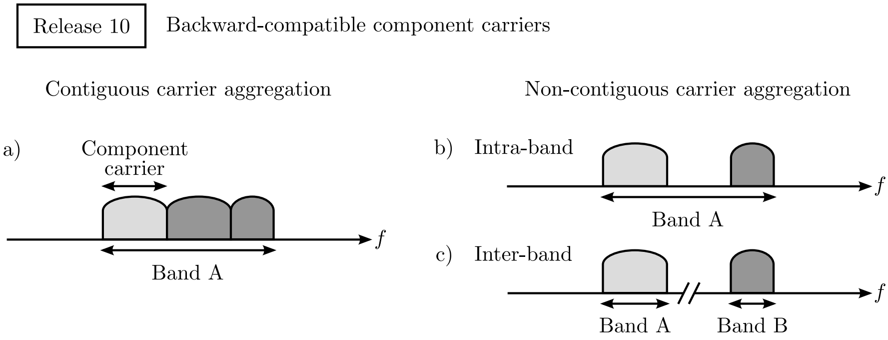

Figure 5.4: Carrier aggregation types in LTE-Advanced Release 10.

radio resources. When adding a new secondary cell, dedicated signaling is used to send all the required system information for the new secondary cell.

It is worth noting that some enhancements for carrier aggregation are currently studied for beyond Release 12. One of these possible enhancements is the definition of New Carrier Type (NCT) in order to increase both spectrum flexibility and spectral efficiency [108]. The main motivation for the definition of the NCT is the use of carriers with minimized transmission of legacy control signaling and common reference signals, which would reduce interferences and signaling overhead.

- Tower overlay over LTE-A system concept

Figure 5.5 shows the tower overlay over LTE-A system concept. Based on FEFs and carrier aggregation, it proposes the use of a hybrid carrier integrating an eMBMS dedicated carrier into a DVB-T2 data stream, which can be transmitted using existing HPHT networks for broadcast service delivery to both fixed and mobile devices.

The feasibility of this approach requires some extension or changes in both systems. Regarding DVB-T2 networks, they need to be extended to support the modulation of LTE Broadcast –eMBMS– signals and their integration into FEFs. It implies the use of hybrid modulators. Concerning LTE/LTE-A networks, it is required to complete the definition of an MBSFN dedicated carrier within eMBMS standard and to support larger CPs. The integration of a dedicated MBSFN carrier into the existing LTE system can be achieved by carrier aggregation, which allows the simultaneous reception of both broadcast and unicast services by using a normal LTE-A unicast carrier as primary cell and the MBSFN dedicated carrier as secondary cell. The reception on the dedi-

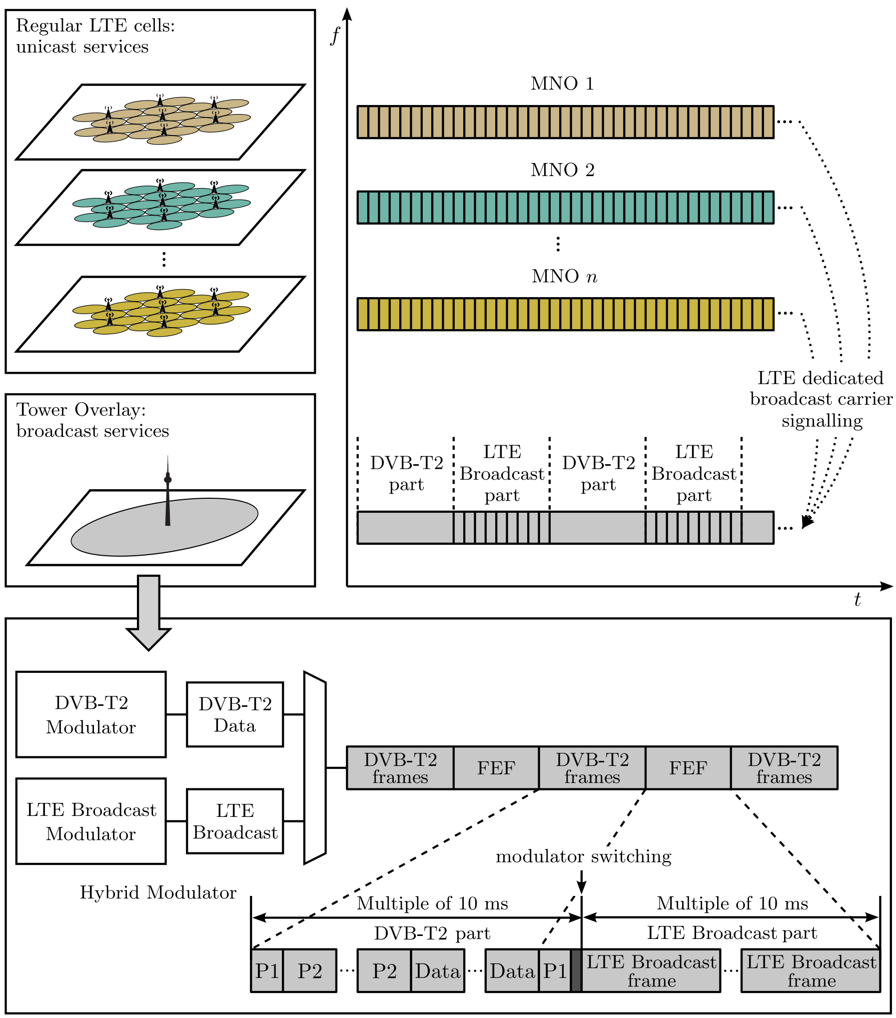

Figure 5.5: A tower overlay over LTE-A with the integration of an eMBMS dedicated carrier into DVB-T2 FEFs.

cated broadcast carrier should be enabled by proper signaling located in the LTE-A unicast carrier. Moreover, the tower overlay resources could be shared by multiple MNOs if all of them inform in their unicast carriers about the availability of dedicated carriers for broadcast services. Moreover, similar to the proposal described before, the coverage area of the dedicated tower overlay carrier is enlarged by defining longer CPs.

In order to comply with the timing regulations of both standards, special consideration is required on the length of the FEFs and T2 frames. Both LTE and DVB-T2 standards operate with different elemental periods defined as the inverse of their sampling frequency. To ensure a constant length of both frames types over a complete T2 super frame, the length of the two different parts in which the hybrid carrier is divided must be an integer multiple of 10 ms, that is, the length of a single LTE radio frame. This fulfills the requirements of the DVB-T2 standard regarding FEF and enables the synchronization between the LTE unicast carrier and the dedicated broadcast carrier. Thus, T2 frames, the initial P1 symbol of the following FEF and a synchronization buffer whose length is an integer multiple of the DVB-T2 elemental period are contained in the DVB-T2 part, whereas the LTE dedicated broadcast part consists of an integer number of LTE radio frames.

5.2.2 LTE Broadcast as ATSC 3.0 physical layer

Currently, ATSC is working on the development of the ATSC 3.0 physical layer. Since most of the proposals take DVB-T2 and/or DVB-NGH as baseline technologies, it is likely that ATSC 3.0 will have significant similarities with these two DVB standards. However, one of the proposals, the one submitted by Qualcomm and Ericsson, is based on LTE Broadcast and proposes some enhancements of eMBMS standard in order to use DTT infrastructure to address both fixed and mobile use cases [101].

A key motivation of this proposal is the announced intentions to deploy LTE Broadcast by multiple MNOs worldwide, where Qualcomm and Ericsson support these efforts with end-to-end integrated solutions. Moreover, eMBMS provides an all-IP solution and, with some enhancements on the physical layer, it could be adapted for traditionally fixed TV broadcast services.

For LTE/LTE-A Release 12, Qualcomm proposed a work item to 3GPP in order to improve the eMBMS efficiency from the radio access perspective [109]. In particular, it proposed the use of longer CPs for large SFN delay spread environments and the adoption of the MBSFN dedicated carrier option completing the upper layer support. The definition of a dedicated carrier would enable new MBSFN use cases, where the control information would be delivered on another –unicast or mixed– carrier. However, this work item proposal was not considered by the 3GPP.

The ATSC 3.0 physical layer is currently under development being this process not public. However, it is likely that the proposal from Qualcomm and Ericsson, based on eMBMS enhancements, goes in the same direction as the 3GPP work item proposal. That is, to complete the definition of eMBMS dedicated carriers and to define longer CPs to address deployment scenarios using HPHT broadcasting networks.

5.3 Challenges for a future mobile converged network

Historically, the business modeling for mobile broadcasting has not been attractive, being the absence of a clear and viable economical model that resolves the monetary conflicts between cellular and broadcast operators one of the main issues behind the failure of mobile TV services [110]. However, both industries are separately taking steps towards the definition of broadcast solutions to cope with future mass mobile multimedia services.

On the one hand, mobile industry has nowadays a good opportunity with eMBMS and its future evolutions thanks to the worldwide adoption of LTE and LTE-A as 4G mobile broadband communications. As commented in the previous section, some of the most important aspects that should be addressed in the evolutions of eMBMS would be the support of dedicated carriers for broadcast services and its deployment over HPHT networks. On the other hand, the common working scenario for the future generation of broadcast terrestrial systems proposed by the FOBTV initiative would help broadcasters to take benefit from the global economies of scale. It is worth noting that the benefits of a global DTT standard capable of supporting both rooftop and mobile reception can be achieved without the need to develop such new global standard. This goal can be achieved if the latest terrestrial broadcast standards are quite similar in such a way that the implementation of several technologies in only one chip is profitable. In that case, DVB-T2 would be the baseline technology.

Assuming the success of FOBTV initiatives to create the common scenario for the worldwide DTT standard and the unified chipsets are also implemented in mobile devices like tablets and smartphones, broadcasters would continue with the problem that their existing HPHT networks cannot provide good coverage to mobile devices and indoor users. This way, broadcasters should deploy new infrastructure to address these use cases. For broadcast industry, the deployment of this new infrastructure without cooperating with MNOs would entail a meaningful investment. In addition, there would be a conflict regarding the provision of mobile TV services as broadcast operators could be opposed to the provision of their services by MNOs.

Another alternative for broadcasters is the adoption of a new technology based on enhancements of LTE eMBMS, which is precisely the proposal of

Qualcomm and Ericsson for ATSC 3.0. However, aside from the lack of infrastructure to provide services to mobile devices, one of the main drawbacks of this alternative would be the opposition of MNOs if this new broadcast technology is not developed within the framework of the 3GPP.

In case of broadcasters take any of these alternatives, it is quite likely that mobile and broadcast industry, with their own regulations, market structure and dedicated network infrastructure to provide their respective set of services, will compete for market and spectrum. However, the trends for cooperation mentioned before highlight the mutual benefit of a complementary use of both networks. The definition of the future 5G system has the potential to delete the border between the two "worlds" and may require innovative approaches to deliver content to end users in the most efficient way from a technical, economic and social perspective. Future 5G system brings a new opportunity for convergence which would benefit both industries alike. For the success of this approach, it is essential that the converged solution addresses the problems regarding network infrastructure and business models existing in the other alternatives.

5.3.1 Spectrum usage: from a problem to a solution

Future 5G mobile communications systems are required to make a flexible and efficient use of the available spectrum, whether contiguous or not, supporting wildly different network deployment scenarios [97].

On the one hand, the UHF band is the core band for terrestrial television, although this band is also used for audio Programme Making and Special Events (PMSE). In particular, the UHF broadcasting band (470-862 MHz) was in the past primarily intended for the provision of analogue terrestrial broadcasting TV. Later on, the development of digital broadcasting technologies allowed the introduction of DTT and the switchover from analogue to DTT has released a significant amount of spectrum in UHF [16]. On the other hand, the mobile industry has always been interested in the UHF band due to its good propagation characteristics and its wavelength suitable for both indoor reception and integration in small devices.

Nowadays, there are contentions on spectrum in the UHF band between both mobile and broadcast industries. In the WRC-07, the 800 MHz band in Region 1 –790 to 862 MHz– and the 700 MHz band in Region 2 and Region 3 –698 790 MHz– was allocated to IMT technologies. This reallocation requires additional guard bands to avoid interferences between cellular and broadcast technologies. In addition, the allocation of the 700 MHz band in Region 1 –694 to 790 MHz– to IMT technologies is on the agenda for the next WRC-15. Table 5.3 shows candidate bands for IMT under WRC-15 agenda [15]. Aside

Table 5.3: Possible candidate bands for IMT under WRC-15 Agenda Item 1.1.

Spectrum bands	**Current user**	**WRC-15 target**
Parts of 500-600 MHz [470-around 694 MHz]	TV Broadcasting, PMSE	Regional identification for IMT usage. Need cooperation with broadcast industry
700 MHz [694-790 MHz]	TV Broadcasting, PMSE	IMT identification for Region 1. Proposed in WRC-12 and included in the WRC-15 AI 1.2
Parts of 1.4 GHz [1350-1525 MHz]	Digital Radio, Fixed Service, Scientific	Global identification for IMT usage. Scientific use, only in a part of frequencies and some parts of regions
2700-2900 MHz	Radar	Global identification for IMT usage
3.4-3.6 GHz	IMT, Satellite	Global identification for IMT usage
3.6-3.8 GHz	IMT, Satellite	Global identification for IMT usage
Parts of 3.8-4.2 GHz	Satellite	Global identification for IMT usage
Parts of 4.4-4.99 GHz	Satellite	Global identification for IMT usage

from the 700 MHz band in Region 1, the band 470-694 MHz, currently used by broadcasters, is also a candidate band for IMT technologies.

Obviously, the release of frequencies for mobile services in many countries where the DTT services have an important penetration will require a costly retune of networks and receiver infrastructures by broadcasters. Moreover, the access to sufficient UHF spectrum is still essential in maintaining existing DTT networks for the introduction of new generation broadcast standards, which will enable service to smartphones and tablets.

By developing a single 5G standard to cope with both mobile a broadcast industry demands, an optimum usage of the spectrum based on spectrum sharing would be enabled. A coordinated spectrum access, as opposed to a competitive and mutually-interfering access, would also render infrastructure sharing and simplified international frequency coordination.

5.3.2 New opportunities and attractive business models

5G could smooth out current dissension between industry players and prepare for a new converged industry, with new class of services and new business models in which all parties, mobile network operators, content providers, broadcasters, spectrum holders and advertisers, could benefit from this convergence solution and offer a full alternative to terrestrial TV broadcasting as a universal service. It is important that the new business models consider the reuse of the existing infrastructure without the need to deploy new one, which is basic to the efficient provision of services.

Besides, current broadcast and mobile broadband networks are complementary and can be used in cooperation very effectively in order to support the evolving consumer demands, thus paving the way towards a complete convergence and synergism in the future (win-win strategies). The combination of the two modes of delivery in 5G enables the easy introduction of new advanced services and applications and supports successful convergent offerings between digital TV broadcast providers and mobile broadband service providers.

Regarding the mobile industry, the higher transmission efficiency of broadcasting as compared with unicast delivery would reduce network overload while diminishing the Capital Expenditures (CAPEX) associated with the ultra-dense deployment of transmission points. Moreover, the possibility of sharing spectrum would reduce the investment in spectrum auctions, improve the quality of service and enable new services and revenues. Concerning broadcasters, the definition of a worldwide DTT standard would boost economies of scale enabling the integration of mobile TV into handheld devices. This will make current broadcasting services grow in terms of scope and availability. In addition, the future 5G networks could also be used to provide TV services to fixed receivers, which would entail the implementation of mobile cellular chips into TV sets.

5.3.3 Requirements for successful convergence

Although last generations of broadcast and mobile systems are quite similar in their fundamentals –e.g., they are OFDM-based–, the optimal radio configuration comprising signaling, procedures and transmission modes is different for broadcast services due to its particular features. Future 5G networks must address several requirements for a successful convergence of both industries.

Firstly, the converged solution in 5G shall include a flexible and scalable broadcast mode able to allow for the transmission of mass multimedia services to mobile and stationary receivers through different network infrastructures. This broadcast mode shall support the efficient transmission of mobile

High Definition Television (HDTV) services. In addition, it shall support the use of traditional broadcasting HPHT infrastructure to increase the coverage range and should be able to share the same frequency used for transmitting fixed Ultra High Definition Television (UHDTV) services using time multiplexing. The future air interface shall be flexible enough to accommodate different sharing scenarios by using dynamic profiles that could switch from unicast to broadcast mode. In this sense, some radio functions could be activated/deactivated/modified on demand depending on the specific needs of the service and the status of the network.

5.4 Conclusions

This chapter has reviewed the state of the art and the current trends on mobile multimedia broadcasting and promoted the convergence of cellular and broadcast networks in the future 5G mobile networks. Although the integration of both networks is on the roadmap of mobile and broadcast industries, there are still some challenges that have been identified throughout this chapter.

Potential enablers for such convergence are the FEFs of second generation DVB networks, which allows combining in the same frequency broadcast and cellular transmissions via time multiplexing, or the carrier aggregation feature of LTE-A, which allows temporarily using a broadcast frequency for cellular transmissions. However, the main issue is that LTE broadcast eMBMS technology does not incorporate a sheer broadcast mode and especially that it cannot be efficiently deployed in HPHT traditional broadcasting infrastructure due to their short guard intervals. Those considerations should be the starting point for the definition of a joint solution within the 5G framework.

Nowadays, broadcasters are taking steps to work in a common scenario for the future generation of broadcast terrestrial system in order to take benefit from the global economies of scale. However, although the global DTT standard is supported in mobile devices, the lack of infrastructure to provide good coverage to tablets and smartphones will continue existing and the deployment of new infrastructure would imply a high investment.

The convergence in 5G would benefit both industries alike. The development of a single 5G standard that copes with both mobile a broadcast industry demands would enable an optimum usage of the spectrum based on spectrum sharing. It could also smooth out current dissension between industry players and prepare for a new converged industry, with new class of services and new business models in which all parties could benefit from this convergence solution and offer a full alternative to terrestrial TV broadcasting as a universal service.

Chapter 6

Conclusions and future work

6.1 Concluding remarks

This dissertation has investigated the use of broadcasting technologies in 4G mobile broadband networks and beyond. Specifically, the dissertation has focused on Evolved Multimedia Broadcast Multicast Services (eMBMS), the broadcast technology included in 4G LTE and LTE-A networks. Our investigations have focused in all aspects related to the eMBMS technology, from physical layer to application layer. For this end, this dissertation has employed a complete simulation platform including link-level and system-level simulations to evaluate the performance of broadcast transmissions in these real technologies.

One of the main issues of eMBMS at the physical layer is the use of Multimedia Broadcast Multicast Services over Single Frequency Networks (MBSFNs). Our performance evaluation results regarding MBSFN deployments have shown that increasing the MBSFN area size always benefits coverage or allows employing a higher Modulation and Coding Scheme (MCS). The usage of a higher MCS, and the subsequent higher eMBMS data rate, entails a wider range of services per MBSFN area. In addition, we have identified some features included in other mobile broadcast systems that could be used in eMBMS for enhancing the performance of MBSFN deployments. They are the use of a dedicated carrier where all the subframes are dedicated for broadcast transmission and the use of MIMO schemes to enhance the broadcast service data rate. The performance evaluation results concerning the use of MIMO for broadcast transmissions have shown that MIMO schemes significantly increase the performance of broadcast transmissions for dense mobile broadcast deployments. With typical urban macro cellular deployments with an inter-site distance of 500 m, the increase in maximum broadcast service data rate obtained using spatial multiplexing with two streams is around 59%. Consequently, future releases of LTE eMBMS should include the use of MIMO schemes to exploit their benefits.

eMBMS specifications allows for an optimum delivery of broadcast services, providing flexibility in the configurations of FEC mechanisms to adjust the broadcast transmission to the different types of eMBMS services. The research on the delivery of streaming and file download service over eMBMS has focused on the RRM problem and trade-off between PHY-FEC and AL-FEC. In that case, the investigations have assumed the broadcast transmissions over a carrier shared with unicast services.

Regarding the delivery of streaming services, results have shown that physical layer error correction mechanism should be combined with AL-FEC to increase the coverage level of streaming services. Thus, a higher maximum service data rate can be obtained if AL-FEC is used. However, results have shown that the gain due to AL-FEC depends on the setting of AL-FEC parameters such as the protection period and code rate, the user mobility, and the quality criterion. The maximum service data rate increases with larger protection periods and in scenarios with higher mobility users. However, these large protection periods produce an excessive zapping time that affects the QoS and it is not recommended for streaming services.

For scenarios with larger inter-site distances, a higher protection both at physical and application layers must be applied to the maximum service data rate. The increase of robustness at both layers entails a reduction on the maximum service data rate. In addition, results have shown that a higher interleaving between different channels within the protection period improves the coverage level as it is possible to exploit better the temporal diversity. Also, the effective interleaving is enlarged. However, this effect depends on the speed of the user, since for low mobility users there is little temporal diversity.

Regarding file delivery services, the research has analyzed the duration of the transmission required to guarantee the correct file reception and the reduction in the mean throughput of unicast users with different delivery modes. They are the unicast delivery, the eMBMS delivery and a hybrid approach, which combines a first eMBMS delivery with a post-delivery error repair phase with unicast transmissions. On the one hand, the use of higher MCSs for the eMBMS delivery reduces the file download time, however, in case of the use of a too-high MCS, transmission errors make retransmission necessary and deteriorate the system performance. The hybrid delivery has proven to be the most efficient configuration in terms of file download time, although this further reduces unicast performance.

On the other hand, as an exemplary use case, this dissertation also has investigated the use of LTE networks for the provision of vehicular safety services comparing both unicast and eMBMS delivery modes. Results have shown the significant benefits in terms of resource usage, end-to-end latency and cost delivery saving that can be achieved by using eMBMS for the delivery of road safety services based on Cooperative Awareness (CA) and Road Hazard Warning (RHW) applications.

The main difference between CA and RHW applications is that the former are based on the transmission of periodic messages and the later are event-based. Thus, the capacity required when delivering CA applications is much higher than in the case of RHW applications. Using the unicast delivery for CA, the maximum system capacity is achieved for a low density of vehicles in the motorway. High density of vehicles in the motorway only can be supported by using eMBMS and if the CAM transmission rate is reduced. In addition, the end-to-end delays with unicast mode are reasonable up to a certain number of vehicles in the scenario, where they begin to grow exponentially. On the contrary, the latency of a CAM in the case of eMBMS delivery in downlink does not depend on the number of vehicles and is limited by the eMBMS scheduling period,

The research on this topic has also addressed the problem associated with the support of road safety applications over the current eMBMS specifications. This dissertation has proposed a solution based on a continuous eMBMS service for road safety services together with a dynamic allocation of eMBMS resources for latency and network efficiency reasons. In addition, the support of road safety applications in eMBMS requires the definition of a new delivery method addressed for time-critical requirements. Concerning the architecture, we have analyzed the impact of the ITS backend server and the possibility to merge it with the BM-SC for the feasibility of multi-operator scenarios.

6.2 Evolution of broadcasting towards 5G

This dissertation has analyzed feasible options of convergence between both the mobile and broadcast industries to ensure the success of mobile broadcasting deployments in the future. A separated evolution of the broadcast technologies of both industries would lead to a scenario with two complete different industries, with different network infrastructures and business models competing for market and spectrum. This dissertation has proposed an approach by which the definition of the future 5G mobile broadband communication system could bring together the cellular and broadcast industries to form a single fixed and mobile converged network.

Although the integration of both networks is on the roadmap of mobile and broadcast industries, there are still some challenges that have been identified throughout this dissertation. The different approaches for cooperation between mobile broadband and broadcast industries focus on 3GPP and DVB systems. The potential enablers for such cooperation are the FEFs of second generation DVB networks, which allow combining in the same frequency broadcast and cellular transmissions via time multiplexing, and the carrier aggregation feature of LTE-A, which allows temporarily using a broadcast frequency for cellular transmissions. These approaches propose the enhancement of eMBMS technology based on the incorporation of a sheer broadcast mode and the introduction of larger guard intervals in order to efficiently deploy eMBMS in HPHT traditional broadcasting infrastructure. Those considerations should be the starting point for the definition of a joint solution within the 5G framework.

Nowadays, based on FOBTV initiatives, the broadcasters are taking steps to work in a common scenario for the future generation of broadcast terrestrial system. Thus, the initiatives for a unified terrestrial broadcast standards targeting both fixed and mobile reception could favor economies of scale thus motivating its implementation on mobile devices. However, broadcast industry has the handicap related to the lack of infrastructure to provide good coverage to mobile devices and broadcasters only can address mobile users if they deploy new infrastructure.

In order to solve this drawback, this dissertation has proposed that the convergence solution of both industries in 5G reuses the existing infrastructure, which is essential for the efficient provision of broadcast services. The development of a single 5G standard that copes with both mobile and broadcast industry demands would enable an optimum usage of the spectrum based on spectrum sharing. It could also smooth out current dissension between industry players and prepare for a new converged industry, with a new class of services and new business models in which all parties could benefit from this convergence solution and offer a full alternative to terrestrial TV broadcasting as a universal service.

6.3 Future research issues

Several innovative research topics have been identified in this dissertation. A very hot research topic today is the evolution of the eMBMS standard in order to increase the performance to become viable at more places and for more applications. The evolution of eMBMS must address aspects such as the dynamic switching between unicast and broadcast, which can enable broadcast on demand and offers scalability.

Future research is also needed to increase the flexibility, range and capacity of eMBMS. Current LTE-A users can support the transmission of data over different unicast carriers using carrier aggregation. This dissertation has proposed the support of dedicated carriers for broadcast transmission and their inclusion within the carrier aggregation concept is an interesting research topic. Moreover, the possibility to extend the use of eMBMS over HPHT networks requires a deep analysis and evaluation of the involved physical layer features. In order to increase the capacity of broadcast transmission, future investigations should focus on the use of MIMO and higher modulations like 256-QAM.

Another interesting topic is the use of video codecs with higher efficiency. The study on streaming service delivery performed in this dissertation has assumed the H.264/Advanced Video Coding (AVC) for RTP payload format as specified for eMBMS. Nowadays, the resolutions of TVs, smartphones, and tablet devices are increasing, and this makes even small devices capable of showing high-definition video. These developments require the use of more efficient coding of digital video like the emerging High Efficiency Video Coding (HEVC). The 3GPP Release 12 specifications now include the support for the HEVC video codec providing a technical solution for highly efficient delivery of download, streaming and conversational video services [111]. HEVC provides a remedy for operators to increase quality of experience while at the same time reducing bandwidth consumption of video services, typically by a factor of 2 compared to the best technologies available prior to Release 12.

Finally, one of the hot research topics today is the evolution of broadcasting towards a 5G system. We are nowadays in the process of identifying different technologies for the future 5G and the research on the definition of the broadcast modes within the 5G concept is a clear research line. For example, one of the features identified for the converged solution in 5G is the use of traditional broadcasting HPHT infrastructure to provide mobile and fixed services in the same frequency channel. One of the latest digital broadcasting technology families, DVB, is capable of delivering both fixed and mobile services simultaneously in one radio frequency channel using Time Division Multiplexing (TDM). However, other physical layer technologies like cloud transmission with Layer Division Multiplexing (LDM) are being proposed to be used in next generation digital TV broadcasting system [112]. In this system, a layered transmission structure is used to simultaneously transmit multiple signals with different robustness for different services: mobile, HDTV or UHDTV. Some results show the benefits of a LDM-based system as compared to the single-layer TDM or Frequency Division Multiplexing (FDM)-based systems, as LDM-based system provides much better efficient use of spectrum.

Appendix A

Description of simulators

A.1 Link-level simulator

As commented in Section 2.1.4, there are three different data-transporting downlink physical channels in LTE: the PBCH, the PDSCH and the PMCH. The first one is used to transmit the Master Information Block (MIB), which consists of a limited number of the most frequently transmitted parameters essential for the initial access to the cell. The second one is the main data-carrying downlink physical channel in LTE. It is used for all user data, for broadcast system information which is not carried on the PBCH, and for paging messages. Finally, the latter is designed to carry data for eMBMS.

Before starting this Thesis, the LTE downlink link-level simulator implemented by the Mobile Communication Group (MCG) of the Instituto de Telecomunicaciones y Aplicaciones Multimedia (iTEAM) at the Universitat Politècnica de València (UPV) [113] comprised both PBCH and PDSCH but not PMCH. In order to accomplish the first objective of this Thesis, all features related to the transmission of PMCH were integrated in this link-level simulator platform. This section describes the main aspects of the LTE link-level simulator focusing on the implementation of the eMBMS features.

A.1.1 Simulator structure

Essentially, a link-level simulator is composed by two kind of elements: those needed to perform the physical layer configuration and those related to degradation. The former include aspects such as modulation, coding, channel estimation and diversity techniques among others. The latter are related to noise,

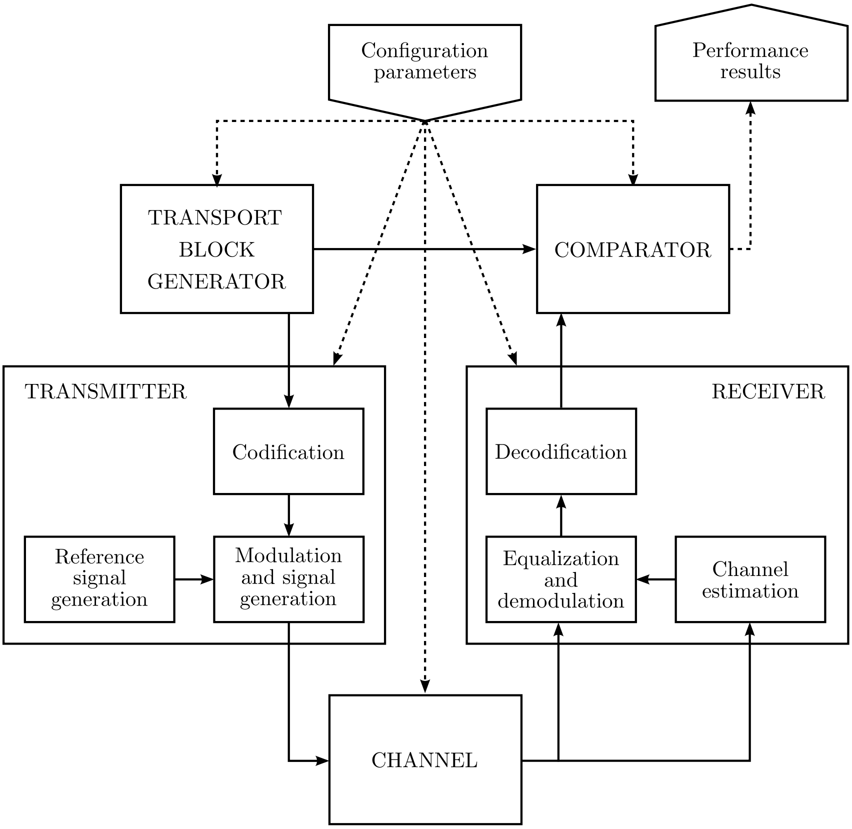

Figure A.1: LTE downlink link-level simulator general structure.

ISI, fast fading due to multipath and the doppler effect associated to the user speed.

Figure A.1 shows the implemented block diagram of the LTE downlink link-level simulator. The simulator has five functional blocks: transport block generator, transmitter, channel, receiver and comparator. These blocks make use of the configuration parameters which are defined by an input file. Finally, an output file is used for simulation results.

In a simulation cycle, one transport block is created by the transport block generator, it is processed at the transmitter, it is sent through the channel, it is processed at the receiver and the received transport block is compared with the original transport block. The number of erroneous bits is obtained through the comparator and, then, Bit Error Rate (BER) and BLER curves can be obtained.

In LTE, the physical layer is communicated with the MAC layer through transport channels. These channels allow physical layer to send transport block of a certain size. The transport block related to eMBMS transmission is the MCH. As LTE specifications defines that the transmission of eMBMS data is only supported with single antenna mode, only one transport block can be transmitted each TTI. In the LTE case, the TTI is defined as one subframe, which lasts 1 ms.

- Transmitter

The transmitter implementation is based on the LTE transmission chain defined in [79] and [114]. Figure A.2 shows the downlink transmission process used for MCH, which is divided in three main blocks. The first one consists of the processes related to coding, the second one is related to the modulation and signal generator processes and, there is another block consisting of the reference signal generation. Firstly, the processes related to coding are the followings:

- Transport block Cyclic Redundancy Check (CRC) attachment: the first step on the MCH transport channel processing is the computation of the CRC. After CRC calculation, it is added at the end of the transport block. In the MCH case, the cyclic generator polynomial consists of 24 bits.

- Code block segmentation and code block CRC attachment: if the transport block size is higher than 6144 bits, the block is segmented in shorter blocks. Each one of the segmented blocks will be treated separately in the next steps. Finally, a CRC is calculated for each segmented block and it is added at the end of the corresponding block.

- Channel coding: in order to correct those errors produced by the channel variability and noise, a channel coding is used. It is performed using a convolutional turbo coder with a code rate of 1/3.

- Rate matching: the goal of the rate matching is to extract or add certain bits so as to adjust to the exact number of bits that can be sent in a TTI. As MBSFN subframes use all available resource blocks to transmit eMBMS data, the total number of bits that can be transmitted depends on the number of OFDM symbols used for control channels and the modulation scheme.

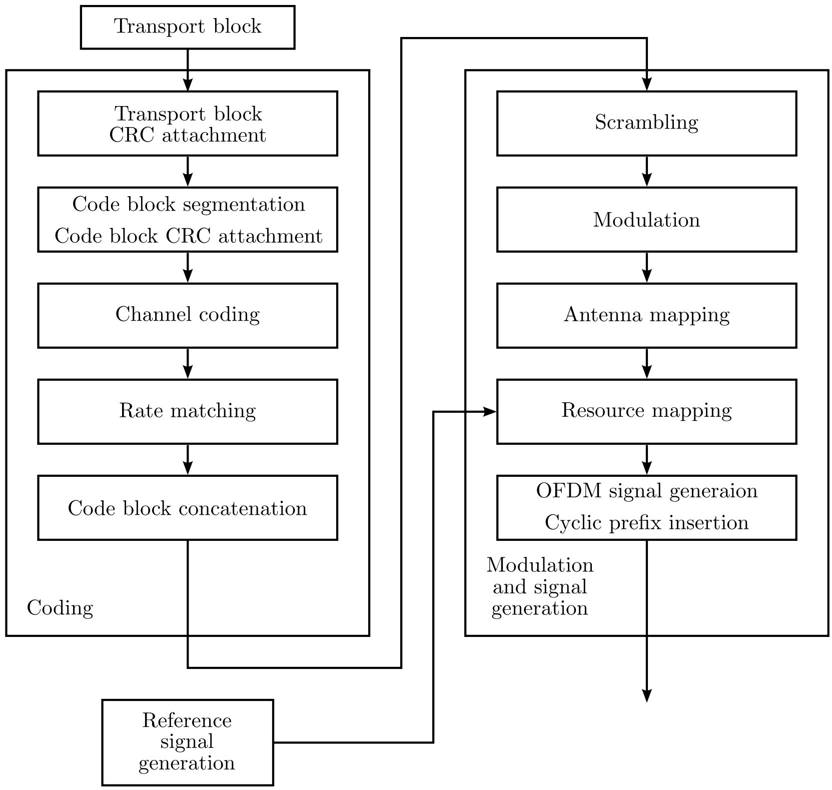

Figure A.2: Block diagram of the transmitter.

- Code block concatenation: in this step, a block resulting on the concatenation in sequence of the outputs related to rate matching block is obtained.

On the other hand, the processes concerning to modulation and signal generator are listed below:

- Scrambling: it lies on the multiplication of bits using a scrambling sequence.

- Modulation: the bits are transformed in complex symbols. Quadrature Phase-Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM) and 64-QAM are the three types of modulations specified in [79].

- Antenna mapping: it is divided in two steps, layer mapping and precoding. The former consists of demultiplexing the modulated symbols in one or more layers. The latter extracts one symbol of each layer, which, firstly, are jointly processed and, then, are transmitted through different antennas. There are several antenna mapping and precoding configurations, which lead to different types of antenna transmission schemes. LTE specifications defines the transmission by means of one single antenna, transmit diversity and spatial multiplexing. In the case of eMBMS data transmission, the single antenna transmission is the only one supported.
- Resource mapping: for each antenna, the generated symbols are mapped in each resource element of the time-frequency grid. However, some resource elements are assigned to reference signals or for control channels.
- OFDM signal generation and cyclic prefix insertion: an Inverse Fast Fourier Transform (IFFT) is used for generating the OFDM signal related to each OFDM symbol. Besides, a CP is added to the signal in time domain.

In order to perform a downlink coherent demodulation, the UE needs to estimate the channel [115]. As commented in Section 2.1.4, LTE system inserts several RSs inside the time-frequency grid to estimate the channel and, particularly for eMBMS transmissions, the MBSFN RSs are used.

- Channel

One of the main differences between fixed and mobile communications systems is the propagation channel. In mobile systems, the radioelectrical propagation takes place through a hostile environment, which experiences random variances in their physical features, which has a high impact on system performance.

Due to the radio waves propagate along different paths from the transmitter to the receiver, the channel is modeled as a set of multi-paths with different characteristics. The radio propagation through a mobile channel can be characterized by means of three phenomena: path loss, exponentially decaying with the distance the wave travelled; slow or long-term fading -also known as shadowing-, which is due to fadings produced by the presence of obstacles in the path between transmitter and receiver; and fast or multipath fading, due to small fluctuations in the channel caused by phase changes in each signal contribution. For link-level simulations, only fast fading is modeled.

More information about the different channel models used in link-level simulations is provided in Section A.1.2. Moreover, a detailed description on the modeling of the three phenomena which characterize a radio propagation channel is provided in Section A.2.3.

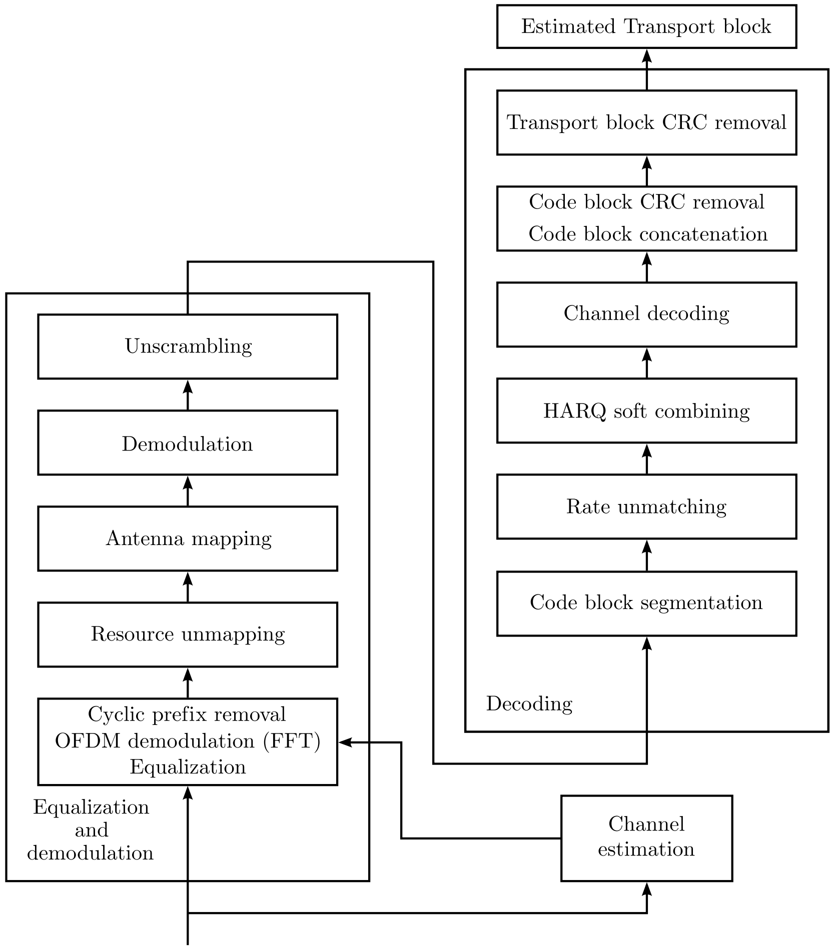

Figure A.3: Block diagram of the receiver

- Receiver

Figure A.3 shows the downlink reception process used for MCH, which is also divided in three main blocks. The first one consists of the processes related to equalization and demodulation, which make use of output of the channel estimation block, and finally, there is another block related to decoding.

The practical implementation of the receiver is opened. Then, many of the building blocks of the system, such as MIMO processing, channel estimation or decoder implementation, can be implemented in different ways and, hence, the performance of a specific system implementation can differ greatly from a system to another.

In addition, the channel variability and the multipath effect require channel estimation. As mentioned before, this channel estimation is performed using reference signals in LTE. In this simulator, several real channel estimators have been implemented [116]. Then, these real channel estimators allow to emulate the penalty on the performance in a real situation due to the channel estimation.

A.1.2 Channel modeling in link-level simulations

As mentioned above, among the three different phenomena which characterize a wireless propagation channel, only fast fading is modeled in link-level simulations. Fast fading accounts for the signal level fluctuations due to constructive and destructive superposition of the multiple signals reaching the mobile terminal. It involves variations on the scale of a half-wavelength, and frequently introduces variations as large as 35 to 40 dB.

The channel modeling at link level is based on specific delay-Doppler power spectrum, which uses power delay profiles extracted from 3GPP [117] to model the time variant small-scale fluctuations of the received signal, and Jakes' Doppler spectrum [118] to model the frequency shifts of the received signal due to Doppler effect. The maximum Doppler can be computed as:

$$f_d = v \cdot \frac{f_c}{c}, \tag{A.1}$$

where v is the receiver speed, f_c is the carrier frequency of the transmission, and c is the speed of light.

Regarding the power delay profiles, the 3GPP defines several propagation conditions that can be used for the performance measurements in multi-path fading environment for low, medium and high Doppler frequencies [117]. The three delay profiles for Evolved Universal Terrestrial Radio Access (E-UTRA) channel models more used in the literature are shown in Table A.1.

However, the channel observed by a UE in MBSFN is quite different than the other cases. In the MBSFN transmission mode, UEs observe multiple versions of the same signal, which correspond to the different simultaneous transmissions from several cells. Then, the evaluation of these type of transmissions through link-level simulations requires a different channel model which emulates the MBSFN operation mode features.

At the beginning, several MBSFN channel models were proposed in LTE. Firstly, the 3xVehicular A (VA) and 3xEVA were presented in [119]. They

Table A.1: Delay profiles for E-UTRA channel models

Model	Number of channel taps	Delay spread (r.m.s.)	Maximum excess tap delay (span)
Extended Pedestrian A (EPA)	7	45 ns	410 ns
Extended Vehicular A (EVA)	9	357 ns	2510 ns
Extended Typical Urban (ETU)	9	991 ns	5000 ns

Table A.2: MBSFN propagation channel profile

Tap	Relative delay (ns)	Average relative level (dB)
1	0	0
2	30	-1.5
3	150	-1.4
4	310	-3.6
5	370	-0.6
6	1090	-7.0
7	12490	-10.0
8	12520	-11.5
9	12640	-11.4
10	12800	-13.6
11	12860	-10.6
12	13580	-17.0
13	27490	-20.0
14	27520	-21.5
15	27640	-21.4
16	27800	-23.6
17	27860	-20.6
18	28580	-27.0

model both the reception of the MBSFN transmission from three cells with different delays and the multipath propagation contributions. However, due to the better correlation properties in frequency domain of 3xEVA, this model was the first one which was chosen for the MBSFN characterization.

Later on, another channel model was proposed. This was the 3xSimplified Extended Vehicular A (SEVA), which was proposed with the aim of reducing the simulation complexity as the three weakest taps in EVA profile were removed. However, in spite of removing these taps, the 3xSEVA channel model conserves the same correlation properties as 3xEVA channel. Then, due to the greater simplicity, the 3xSEVA channel model is the one specified by 3GPP in [117] to assess the MBSFN performance in LTE. In Table A.2, the tap delays and average relative power level of each one related to 3xSEVA channel model are presented.

A.1.3 Transport block sizes modeling

When a LTE subframe is allocated to eMBMS transmission, all system resources are used for the eMBMS physical channel, the PMCH, except the OFDM symbols configured for the PDCCH –one or two symbols– and the MBSFN reference signals. In addition to the resource elements available for eMBMS, the transport block size depends on the MCS used for its transmission.

Similarly to the transport block which carries unicast data, LTE specifications [120] defines 29 different MCSs for eMBMS. In particular there are 10 different modes for QPSK, 7 for 16-QAM and 12 for 64-QAM. Moreover, the PHY-FEC code rate depends on the Transport Block Size (TBS) used for each MCS, which is different for each resource allocation.

In order to simplify the simulations, we have assumed the smaller set of MCSs shown in Table A.3. They correspond to the set of MCSs included in the CQI table of the LTE specifications[120]. There are 15 different modes, 6 for QPSK, 3 for 16-QAM and 6 for 64-QAM.

A.2 System-level simulator

In cellular networks, system-level simulations are used to estimate the QoS experienced by the users in a very detailed manner, giving a better understanding of the network behaviour. System-level simulations allow evaluating the overall system performance perceived by the users statistically with Monte Carlo simulations. This means repeating the same experiment many times with different random seeds and computing the average results (the higher the number of repetitions, the more accurate the results).

Table A.3: MCS configurations based on CQI.

Idx	**Mod**	**Code rate**	**Efficiency**
1	QPSK	78/1024	0.1523
2	QPSK	120/1024	0.2344
3	QPSK	193/1024	0.3770
4	QPSK	308/1024	0.6016
5	QPSK	449/1024	0.8770
6	QPSK	602/1024	1.1758
7	16 QAM	378/1024	1.4766
8	16 QAM	490/1024	1.9141
9	16 QAM	616/1024	2.4063
10	64 QAM	466/1024	2.7305
11	64 QAM	567/1024	3.3223
12	64 QAM	666/1024	3.9023
13	64 QAM	772/1024	4.5234
14	64 QAM	873/1024	5.1152
15	64 QAM	948/1024	5.5547

In the particular case of eMBMS, such system-level simulations can be used as a complement of traditional coverage planning tools for mobile broadcasting networks for analyzing QoS and RRM aspects of the transmission configuration. For example, it would be possible to monitor the time evolution of the errors of a video streaming service perceived by the users, or determine the user that successfully receive a file. Another application would be to evaluate the influence of the MBSFN area sizes not only in terms of area coverage, but also in terms of QoS perceived by the users.

This section describes the system-level simulator used in this dissertation, which has been developed by the MCG of the iTEAM at the UPV [121]. Concerning this simulator, the work of the author has been the addition of the required eMBMS features to assess the performance at of broadcast transmissions over LTE at system level.

A.2.1 Simulator structure

Figure A.4 shows the structure of the LTE system-level simulator. It can be considered a discrete-event simulator, where network dynamics are represented as a chronological sequence of events, simulated with a slot resolution equal to a TTI. Each TTI, the mobiles' movement and received signal strength are updated and, then, the data received in the transport block can be computed.

The cellular system is modeled in system-level simulations by the different blocks: the network layout, which defines the scenario where the cellular system is deployed; the configuration parameters related to the equipments; the propagation and channel model, which characterizes the radio propagation phenomena; the mobility model, which moves user across the simulation scenario; the traffic model, which generated the data traffic for users.

One of the most important blocks of the system-level simulation is the link measurement model. For each user, it knows the received signal from each eNB, both useful and interfering one, and thus, by knowing the transmitted power,

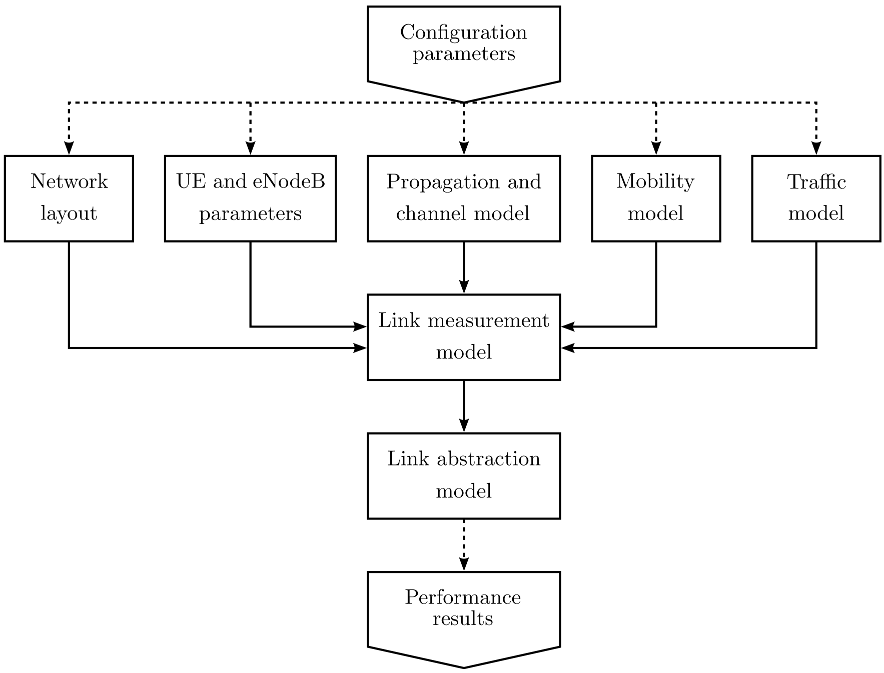

Figure A.4: LTE downlink system-level simulator general structure.

the interference model and its channel model, it can measure the received signal quality.

A detailed description of the different models used in the system-level simulations are provided in the following sections. It is worth noting that the traffic models used for eMBMS, video streaming and file delivery, will be deeply described in the next chapter.

A.2.2 Network layout and equipment parameters

The cellular structure defines the scenario on which the simulations are carried out, establishing the geographic layout of the eNBs which conform the network access of the simulated system.

This dissertation follows the ITU guidelines for the IMT-Advanced candidate evaluation [94]. These guidelines contain test environments and baseline configuration parameters that shall be applied in simulation assessments of Radio Access Technologys (RATs) like LTE or LTE-A.

The test environments considered in these guidelines are four: indoor, microcellular, base coverage urban and high speed. The deployment scenario used for these test environments, except for the indoor, is a synthetic scenario where the base stations are placed in a regular grid, following hexagonal layout. Figure A.5 shows the basic hexagon layout of 19 sites, each of 3 cells, where basic geometry –antenna boresight, cell range, and ISD– is defined.

In this Thesis, the most of the performance assessments are obtained for the base coverage urban environment, also known as UMa scenario in [94], which is the main use case considered for eMBMS deployments. For that scenario, the Base Station (BS) antenna height is 25 m and the ISD is 500 m.

Concerning the system configuration parameters, Table A.4 summarizes the common parameters and assumptions of the equipments, UE and eNB, applied in the different assessments of eMBMS. They follow ITU guidelines and 3GPP specifications. In particular, they are based on the simulation parameters for UMa scenario, where the antenna pattern is modeled taking into account azimuth, elevation and tilt [94].

A.2.3 Channel modeling in system-level simulations

The mobile channel characterization can be addressed from several points of view. The traditional method consists of statistically modeling the random phenomena that take place in the channel, focusing on the attenuation that they produce on the radiated signals. That focus is particularly adequate for the system-level simulations, then, it has been adopted in the channel characterization included in the simulation platform.

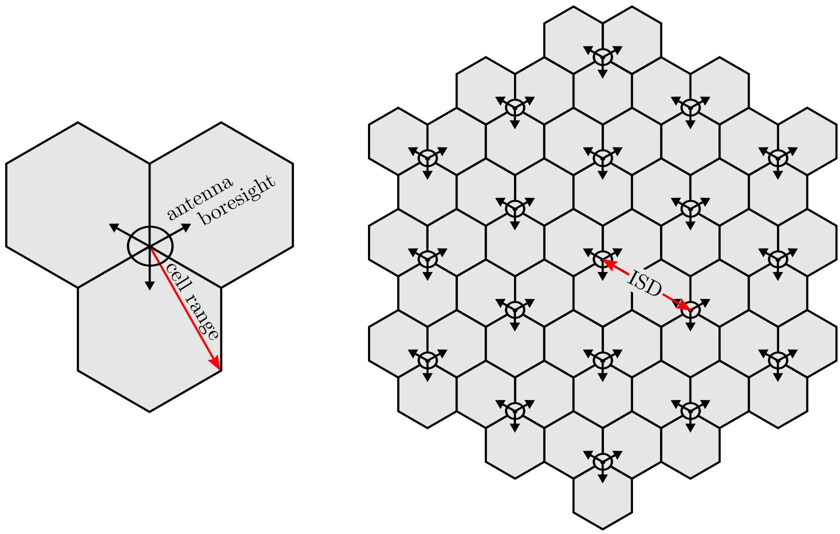

Figure A.5: Urban Macro-cell layout.

As aforementioned, the channel propagation in system-level simulations is modeled by three different phenomena: path loss, shadowing and fast fading.

- Path loss

The path loss provides a estimation of the average losses experimented by the signal. This term is obtained by means of some propagation model that related in a deterministic way the average losses with the environment parameters such as the distance between transmitter and receiver, the frequency of the signal, the height of the antennas and the profile of the terrain.

For large distances, the received signal strength decreases exponentially with the distance, and the path loss can be in general modeled as:

$$L_d = \beta + 10 \cdot \alpha \cdot \log_{10}[d], \tag{A.2}$$

where β is a distance independent term, which depends on the centre frequency, and α is the propagation exponent. For free-space propagation α is equal to 2, but in practice it usually ranges between 3 and 4.

Although ITU guidelines defines several path loss models for the different scenarios considered, we have used the the simplified Okumura-Hata formula for path loss [119] in this dissertation. Using this model at 2 GHz, β and α are 128.1 and 3.76, respectively.

Table A.4: Common simulation parameters and assumptions used for the different eMBMS assessments.

Parameter	Value
Central frequency	2 GHz
System bandwidth	10 MHz
eNB transmission power	46 dBm
eNB antenna tilt	12°
eNB transmission mode	Single antenna transmission
UE receiver	Maximum Ratio Combining (MRC) with two reception antennas
UE noise figure	9 dB
Penetration loss	20 dB
Noise spectral density	-174 dBm/Hz

- Shadowing

The shadowing is a term of random losses that are added to the average losses and represents the effect of the fadings produced by the presence of obstacles in the path between transmitter and receiver which do not have been taken into account in the deterministic propagation model.

It changes more rapidly than the path loss, with significant variations over distances of several tens of meters (comparable to the widths of buildings in the region of the mobile). Shadowing is traditionally assumed to be log-normally distributed. That is, the distribution of the signal power is log-normal (the signal measured in dB follows a normal or Gaussian distribution). It is also sometimes referred to as log-normal fading.

The spatial variation of the shadowing in dB is described by a zero-mean Gaussian random variable with standard deviation σ_l and correlation distance d_{corr}. The standard deviation of the shadowing distribution is known as the location variability, and it determines the spread of the signal field strength around the mean value. Its value increases with frequency, being greatest in suburban areas and smallest in open areas. It is usually in the range of 5 to 12 dB. Spatial correlation of shadowing is usually modeled using a first-order exponential model:

$$\rho\left(d\right) = e^{-d/d_{corr}}, \tag{A.3}$$

where d_{corr} is a distance taken for the autocorrelation to fall by e^{-1}.

In order to simulate correlated shadowing, we have used a log-normal map defined by its σ_l and d_{corr} where users move across it. With this method, a shadowing map is generated for each transmitter, which ensures that two users in close vicinity experience similar obstruction.

- Fast fading

The fast fading is due to the multipath effect. It consists of that multiple contributions of the transmitted signal that suffer different scattering and diffraction processes are received. Each one of these contributions present different incidence angles, attenuation, phase differences and propagation delays. Their combination at the receiver originates fast and deep fadings in the received signal.

Similarly to link-level simulations, the fast fading modeling at system-level simulations is based on specific delay-Doppler power spectrum. However, we cannot use the MBSFN channel model reference shown in Table A.2 in system-level simulations due to this model assumes a SFN of three cells. Then, in order to model the MBSFN transmission mode at system level for different MBSFN area sizes, an OFDM signal combining model is required. This model predicts, for each user, how signals from the different sites contribute to the useful received signal or cause self-interference at each location.

In MBSFNs, interference consists of both external interferences and self-interference from the own network. For small-size networks, self-interferences are negligible, but they cannot be neglected in a dense MBSFN. Signals received within the OFDM symbol guard interval are considered as useful and contribute totally to the useful signal, whereas signals with a time delay larger than the guard interval cause self-interference. In practice, signals arriving with a slightly longer delay than the guard interval contribute partially to the useful signal and partially to the self-interference. Usually, a weighting function according to the signal delay $w\left(\tau\right)$ is employed to determine the ratio between the useful and interfering contribution [19, 122]. The impact of the signals from an eNB is therefore related to the propagation delay defined as:

$$\tau_i = \frac{d_i - d_0}{c}, \tag{A.4}$$

where d_i and d_0 are the distance from the user to the eNB i and to the eNB taken as reference, respectively, and c is the speed of light.

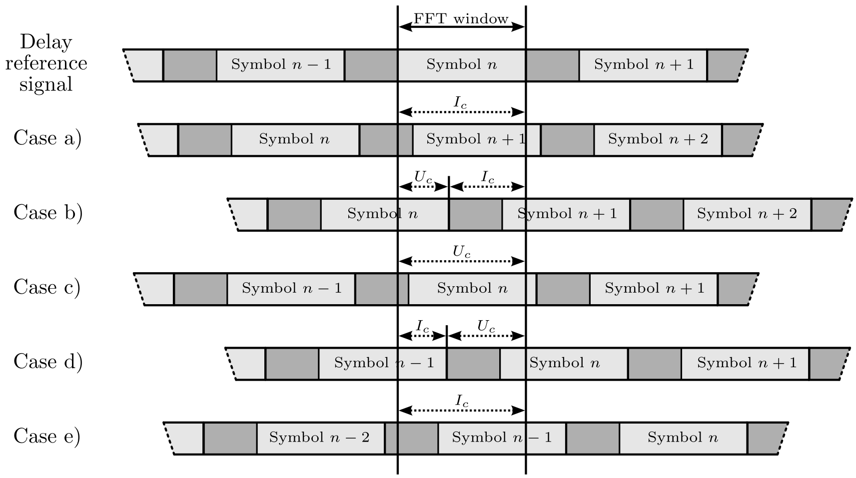

Figure A.6: Possible received signal delays splitting the contribution of received signal into useful and interfering components.

Then, for each delay τ_i we assign a numerical value representing the percentage that a given received path falls within the FFT window. Figure A.6 shows all cases that can take place be an example of the different signals. The weighting function $w(\tau)$ is defined as:

$$w(\tau) = \begin{cases} 0 & \tau < -T_u \\ 1 + \dfrac{\tau}{T_u} & -T_u \leq \tau < 0 \\ 1 & 0 \leq \tau < T_{CP} \\ 1 - \dfrac{\tau - T_{CP}}{T_u} & T_{CP} \leq \tau < T_{CP} + T_u \\ 0 & otherwise \end{cases} \tag{A.5}$$

The performance of the receivers will strongly depend on the synchronization strategy used to determine the time synchronization point (FFT window time position). The optimum FFT window time position where the effective SINR is maximized cannot be easily found, and in general would take too much time to be calculated. Therefore, normally a simpler strategy is applied, such as synchronizing to the strongest signal, or synchronizing to the first received signal that exceeds a given threshold. In that case, $\tau = 0$ is defined at the beginning of the CP.

A.2.4 Mobility model

Mobility models describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time. Since mobility patterns may play a significant role when evaluating the system performance, it is in general desirable that the model is based on real traffic patterns of the scenario under study, or at least that the movement is emulated in a reasonable way.

In this dissertation, two different assumptions regarding mobility are considered. On the one hand, we performed semi-static simulations as defined in [94]. In this procedure, users are randomly dropped in the simulation scenario and do not change their position, which results in a unique path loss and shadowing value for each user, although channel frequency response is evolving in time according to the assumed user speed.

On the other hand, users are randomly dropped in the simulation scenario and move according to the mobility model proposed in [123]. It is a statistical model for vehicular users relatively simple to implement but still able to provide realistic street patterns and terminal movements. The model captures the users' movements with three random variables: street distance, direction change at crossroads and average velocity. These three variables are used to find an analytical formulation. This model was also used in [84] and, in this dissertation, also is used for pedestrian mobility.

Basically, the model assigns to the users a new velocity, street distance, and a relative change in direction when they finish moving across their current street. The model provides different distribution functions with a limited number of parameters that can be easily derived for a particular city. The relative direction changes at crossroads are expressed by four random variables associated to turning left p_{-90°, right p_{90°, round p_{180°, and continuing straight ahead p_{0°. They are assumed to be normally distributed with the same standard deviation σ_φ, equal to $pi/32$. The street distance random variable is assumed to be Rayleigh distributed, with average length $\bar{d}$. Finally, the users' speed is modeled according to a Rayleigh/Rice distribution to distinguish between urban streets and major roads. The velocity parameters are the mean velocities of city and major roads, $\bar{v}$ and $\bar{v}_{mr}$, velocity deviation σ_v, and percentage of cars on major roads p_{mr}.

A.2.5 Link measurement modeling

One of the most important functions in the system-level simulator is the calculation of the SINR obtained in the UE after the receiver filter and before the decoder. Different receiver filters have been modeled: for Single-Input Multiple-Output (SIMO) the MRC is used while for MIMO –used in the broadcast mode of the IEEE 802.16m standard– the Minimum Mean Square Error (MMSE) receiver with interference suppression or interference cancellation is considered. The implementation of theses receiver filters for eMBMS are based on the per-tone post processing SINR of [78] but considering that the signal of several base stations contribute to the useful signal.

A.2.6 Link abstraction models

As aforementioned, in order to reduce the simulation complexity, simulations are usually divided into two stages or levels of abstraction known as link-level and system-level simulations.

The main reason for that consists of the different required time resolution in both levels. On the one hand, extended system-level simulations of at least 10-20 minutes are required to obtain acceptable statistics of the random models of traffic and mobility. On the other hand, at link level, it is required an OFDM symbol level resolution to obtain an appropriate radio link characterization. If this temporal resolution was considered in system-level simulations, the simulator computational cost would be unaffordable.

The interaction between both simulation levels is carried out through the use of interfaces, using the link-level simulation results as input data for the system-level simulations. The behaviour of a transmission at a link level is represented by means of a set of tables known as Look-Up Tabless (LUTs). These LUTs are only numerical tables in which a relationship between the experimented quality at the radio link (e.g. SINR) and its corresponding error rate (e.g. BLER) is established.

In this Thesis the Mutual Information Effective SINR Mapping (MIESM) model has been chosen [124] as link abstraction model. Using this model, the multiple SINR obtained at system level for a specific link are translated to an effective SINR value in a first step and later converted to a BLER value in a second step. The latter step requires the availability of SINR to BLER mappings in Additive White Gaussian Noise (AWGN) conditions for each MCS. These mappings are obtained through link-level simulations.

A.2.6.1 Mutual Information Based Effective SINR Mapping

In general, the Effective SINR Mapping (ESM) Physical layer (PHY) abstraction methods can be described as follows [78]:

$$SINR_{eff} = \Phi^{-1} \left\{ \frac{1}{N} \sum_{n=1}^{N} \Phi \left(SINR_n \right) \right\}, \tag{A.6}$$

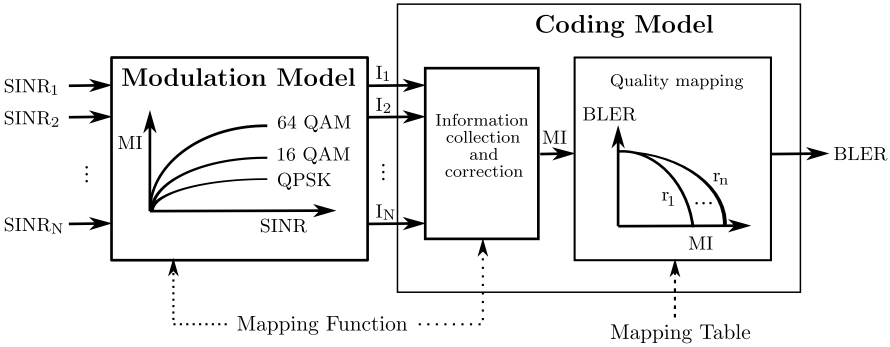

Figure A.7: Computational procedure for MIESM method.

where $SINR_{eff}$ is the effective SINR, $SINR_n$ is the SINR in the n^{th} subcarrier, N is the number of subcarriers in an OFDM system and Φ is an invertible function. In the case of the MIESM the function $\Phi(\bullet)$ is derived from the constrained capacity.

It is worth noting that N depends on the frequency separation between two consecutive samples. The larger the number of samples, the higher the computational cost of simulations. Instead of obtaining one sample per frequency subcarrier, we assumed one SINR value for each RB in order to simplify the simulations.

Figure A.7 shows a block diagram which represents the computational procedure for MIESM method [78]. The input of this method is a set of N received encoder symbol SINR values ($SINR_1, SINR_2, SINR_3, \ldots, SINR_N$) obtained from system-level simulation. The different steps to map the set of SINR values to one BLER value are described below:

1) A Symbol Mutual Information (SI) value is obtained for each one of the SINR values using a SINR to SI mapping function. There are three different SINR to SI mapping function, one for each modulation order (QPSK, 16-QAM and 64-QAM). These functions are previously calculated using system simulations as defined in [78].

2) A Mutual Information (MI) metric is computed from the set SI values. It is obtained as the mean of the SI values.

3) An effective SINR value is calculated from the MI value using the inverse of the SINR to SI mapping function.

4) An BLER value is obtained from the effective SINR value by using the AWGN link performance curves used to map SINR into BLER values.

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