Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems

Deliverable D3.1

LTE-Advanced Pro Broadcast Radio Access Network Benchmark

Version v1.1 Date: 2018/06/29

Document properties:

Grant Number:	761498
Document Number:	D3.1
Document Title:	LTE-Advanced Pro Broadcast Radio Access Network Benchmark
Editor(s):	David Vargas (BBC) and De Mi (UNIS)
Authors:	Irene Alepuz, Carlos Barjau, David Gomez-Barquero, Eduardo Garro, Jordi Joan Gimenez, Jose Luis Carcel, Jose F. Monserrat (UPV); Athul Prasad, David Navrátil, Mikko Säily (Nokia); David Vargas, Simon Elliott, Andrew Murphy (BBC); Tuan Tran (Expway); Heikki Kokkinen (Fairspectrum); Javier Morgade, Khishigbayar Dushchuluun, Peter Renka (IRT); Peter Sanders (One2many); Volker Pauli, Fasil Tesema (Nomor); Manuel Fuentes, Louis Christodoulou, Belkacem Mouhouche (Samsung); Giovanna D'Aria (TIM); Tero Jokela (TUAS); Darko Ratkaj (EBU); Hongzhi Chen, De Mi (UNIS)
Contractual Date of Delivery:	2017/11/30
Dissemination level:	Public
Status:	Final
Version:	1.1
File Name:	5G-Xcast_D3.1_v1.1

Abstract

This report defines technical requirements for the WP3 on Radio Access Network (RAN) for the use cases of the four vertical sectors on Media & Entertainment, Public Warning, Automotive, and Internet of Things. The selection of the Key Performance Indicators (KPI) and evaluation methodology for the RAN benchmark has been aligned with one defined by the ITU-R for the IMT-2020 RIT evaluation process. The main target in the performance evaluation of the technical KPIs has been the technical standard 3GPP Rel'14 LTE-Advanced-Pro specification for both Point-to-Point (PTP) and Point-to-Multipoint (PTM) transmission modes. For PTM the evaluation has included SC-PTM, eMBMS (MBSFN) and ATSC 3.0 systems. The selected test environments are representative of the WP2 use cases and are also aligned to the test environments as defined in the IMT-2020 evaluation guidelines. The performance evaluation will serve as the benchmark to compare with the performance of 5G-Xcast new radio solutions developed throughout the project.

Keywords

3GPP LTE-Advanced Pro, Point-to-Multipoint, Point-to-Point, Radio Access Network, 5G-Xcast RAN Technical Requirements, Key Performance Indicators, Link Level Simulations, System Level Simulations, Coverage Simulations, Media & Entertainment vertical, Public Warning vertical, Automotive vertical, IoT vertical, IMT-2020 evaluation, Air interface limitations, RAT protocols limitations, Spectrum limitations.

Revision History

Revision	Date	Issued by	Description
V1.0	2017/11/30	David Vargas	First public version
V1.1	2018/06/29	David Vargas	Updated version with changes in sections 1.4, 4.4.3, 4.4.4, 5.2.2, 5.5, A.5 and a new annex E.

Disclaimer

Executive Summary

This document evaluates the performance of the latest radio enhancements of eMBMS LTE-Advanced Pro as per 3GPP Release-14, within which 3GPP has added features to enable mobile networks to deliver television services in new and improved ways. The performance evaluation, via extensive link level, system level and coverage simulations, will serve as the benchmark against which to compare the performance of the 5G-Xcast new radio solutions that are to be developed throughout the Project.

Focusing on the radio access network (RAN), the use cases identified in Work Package 2 (WP2) in the 5G-Xcast project are reviewed and technical requirements are specified from the radio point of view. These technical requirements will be used as the basis for evaluating the state-of-the-art technologies and new developments within the Project.

This document also has the objective to identify technical limitations of the LTE-Advanced-Pro Broadcast RAN in terms of the air interface, radio access technology protocols and spectrum. This then makes it possible to outline potential technologies, procedures and areas of research to overcome such limitations in the ensuing tasks within the 5G-Xcast project.

For the RAN benchmark in this Work Package, technical Key Performance Indicators (KPIs) are identified that are relevant to the aforementioned use cases and aligned to the evaluation methodology defined by the ITU-R for the IMT-2020 radio interface technology evaluation process.

The performance evaluation of the selected KPIs targets the recently standardized 3GPP Release-14 LTE-Advanced Pro specification for both point-to-point (PTP) and point-to-multipoint (PTM) transmission modes, since most of the relevant use cases identified in this project require a combination of both unicast and multicast/broadcast components.

For PTM the evaluation includes the state-of-the-art technologies SC-PTM, eMBMS (MBSFN) and the latest terrestrial broadcasting standard ATSC 3.0. For the different KPIs, the evaluations are performed by an analytical procedure, an inspection procedure or by a simulation procedure as appropriate.

In particular, link level, system level and coverage simulations investigate the performance for different transmission parameters and environments (e.g., dense urban, rural, indoor, mobile and fixed rooftop antenna). The selected environments are representative of the WP2 use cases and are also aligned to the test environments as defined in the IMT-2020 evaluation guidelines.

The evaluations carried out in this report indicate that various techniques could serve to significantly enhance the performance of the existing PTM alternatives in the LTE-Advanced Pro (Release-14) specification.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
3G	3th Generation
4G	4th Generation
5G	5th Generation
ADTs	Application Data Tables
AL-FEC	Forward Error Correction at Application Layer
AMC	Adaptive Modulation and Coding
ASO	Analog Switch-Off
ATSC	Advanced Television Systems Committee
Auto	Automotive
AWGN	Additive White Gaussian Noise
BCH	Broadcast Channel
BCCH	Broadcast Control Channel
BER	Bit Error Rate
BICM	Bit-Interleaved Coded Modulation
BIL	Bit-Interleaving
BLER	Block Error Rate
BS	Base Station
BW	Bandwidth
CA	Carrier Aggregation
CAS	Cell Acquisition Subframes
CB	Channel Bonding
CBRS	Citizen’s Broadband Radio Service
CC	Component Carriers
CDF	Cumulative Distribution Function
CEPT	European Conference of Postal and Telecommunications
CFI	Control Format Indicator
CFR	Channel Frequency Response
CMAS	Commercial Mobile Alerts
CNR	Carrier-to-Noise Ratio
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
CT	Core network and Terminal
DASH	Dynamic Adaptive Streaming over HTTP
DC	Direct Current
DCI	Downlink Control Information
DL-SCH	Downlink Shared Channel
DTT	Digital Terrestrial Television
DUT	Devices Under Test
DVB-T	Digital Video Broadcasting – Terrestrial
DVB-T2	Digital Video Broadcasting – 2nd Generation Terrestrial
eLAA	enhanced LAA
eMBB	enhanced Mobile Broadband
eMBMS	enhanced Multimedia Broadcast Multicast Service
eMTC	enhanced Machine Type Communication
eNB	eNodeB
ECB	Equivalent Complex Baseband
EC-GPRS	Extended Coverage GPRS
EnTV	Enhancements for Television Service
ESR	Errored-Second-Ratio
ETWS	Earthquake and Tsunami Warning System
ETSI	European Telecommunications Standards Institute
EU-Alert	Europe Alert
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FEC	Forward Error Correction

FER	Frame Error Ratio
FFT	Fast Fourier Transform
FIL	Frequency Interleaving
FUHF	The Future of UHF Frequency Band
GI	Guard Interval
GPRS	General Packet Radio Service
GSM	Global System for Mobile
HARQ	Hybrid Automatic Repeat Request
HD	High Definition
HPHT	High Power High Tower
i.i.d.	independent and identically distributed
ICI	Inter-Carrier Interference
IMB5	Integration of Mobile and Broadcast in LTE/5G
IMT	International Mobile Telecommunication
IoT	Internet of Things
IP	Internet Protocol
ISD	Inter-Site Distance
ISI	Inter-Symbol Interference
ISM	Industrial Scientific and Medical
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union Radiocommunication sector
KPAS	Korean Public Alert System
KPI	Key Performance Indicator
LAA	Licensed Assisted Access
LDM	Layered Division Multiplexing
LDPC	Long-Density Parity Check
LS	Least Square
LSA	Licensed Shared Access
LPLT	Low Power Low Tower
LTE	Long Term Evolution
LTE-U	Unlicensed LTE
mMTC	massive Machine-Type Communications
MATV	Master Antenna Television
MBMS	Multimedia Broadcast Multicast Service
MBMS-API	eMBMS Application Programming Interface
MBSFN	MBMS over Single Frequency Networks
MCE	Multi-cell/multicast Coordination Entity
MCCH	Multicast Control Channel
MCL	Maximum Coupling Loss
MCS	Modulation and Coding Scheme
MDER	MPEG-DASH Error Rate
MIB	Master Information Block
MIESM	Mutual Information Effective SINR Metric
MIMO	Multiple-Input and Multiple-Output
MMSE	Minimum Mean Square Error
MNO	Mobile Network Operator
MFN	Multi-Frequency Network
MPEG	Moving Picture Experts Group
MooD	MBMS operation on-Demand
MRB	Multi-behaviour and Reliable Broadcast
MTC	Machine Type Communication
MTCH	Multicast Traffic Channel
Multi-RF	Multi-Radio-Frequency
M&E	Media & Entertainment
NB-IoT	NarrowBand IoT
NGH	Next Generation broadcasting system to Handheld
NGH-PI	NGH Portable Indoor
NGH-PO	NGH Portable Outdoor
NOMA	Non-Orthogonal Multiple Access

NR	New Radio
NRAs	National Regulatory Authorities
NUC	Non-Uniform Constellations
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOBE	Out of Band Emissions
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDP	Power Delay Profile
PDSCH	Physical Downlink Shared Channel
PDU	Packet Unit Data
PMCH	Physical Multicast Channel
PPDR	Public Protection and Disaster Recovery
PSM	Public Service Media
PTM	Point-to-Multipoint
PTP	Point-to-Point
PW	Public Warning
PWS	Public Warning System
QAM	Quadrature Amplitude Modulation
QEF	Quasi Error Free
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R	Requirement
RAN	Radio Access Network
RAN1	Radio layer 1
RAT	Radio Access Technology
RE	Resource Element
Rel	Release
RF	Radio Frequency
RIT	Radio Interface Technology
RLC-UM	Radio Link Control-Unacknowledged Mode
RNTI	Radio Network Temporary Identity
ROM	Receive Only Mode
RRC	Radio Resource Control
RSPG	Radio Spectrum Policy Group
SC	Single Cell
SC-PTM	Single Cell – Point-to-Multipoint
SDL	Supplemental Downlink
SDU	Service Data Unit
SE	Spectral Efficiency
SFN	Single Frequency Networks
SI	System Information
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference plus Noise Ratio
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SP	Scattered Pilot
S-PLP	Single Physical Layer Pipe
SRIT	System Radio Interface Technology
TBS	Transport Block Size
TDM	Time Division Multiplexing
TFS	Time Frequency Slicing
TIL	Time Interleaving
TM	Transmission Mode
TR	Technical Report
TRxP	Transmission Reception Point
TS	Technical Specification
TTI	Transmission Time Interval
TU6	6-tap Typical Urban

TV	Television
TVWS	TV White Space
UE	User Equipment
UHD	Ultra-High Definition
UL	Uplink
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable and Low Latency Communications
VoLTE	Voice over LTE
VR	Virtual Reality
V2X	Vehicular to everything
WEA	Wireless Emergency Alert
WG	Working Group
WP	Work Package
xMB	Broadcasting application programming

1 Introduction

1.1 Background and scope

1.1.1 3GPP evolution of PTM communications in 4G LTE

3GPP has enhanced the point-to-multipoint (PTM) communication capabilities of 4G LTE in all releases since the adoption of eMBMS (enhanced Multimedia Broadcast Multicast Service) in Release (Rel') 9 [1].

eMBMS introduced new PTM radio bearers and multicast support in the core network with small changes to the existing radio and core network protocols of LTE. New physical, transport and logic channels were defined to enable single frequency networks, also known as MBSFN (MBMS over Single Frequency Networks), as well as new logical entities in the network architecture.

eMBMS Rel'9 was largely based on the original MBMS technology standardized for 3G in Rel'6 [2], which was initially conceived as an add-on mobile television (TV) service in a large pre-planned area with a rather static configuration. Since its introduction, eMBMS has gone through a very significant set of enhancements. Rel'14 is very different from the first version of eMBMS developed in Rel'9, but it carries a long legacy due to the backwards-compatible design philosophy of 4G LTE. For example, the usage of always-on signalling such as cell-specific reference signals, synchronization signals, etc., which were defined as mandatory requirements in LTE Rel'8 required the definition of special MBSFN subframes and a new physical channel.

Figure 1 depicts the evolution of PTM transmissions in 4G LTE. The main enhancements from a RAN perspective are briefly explained next.

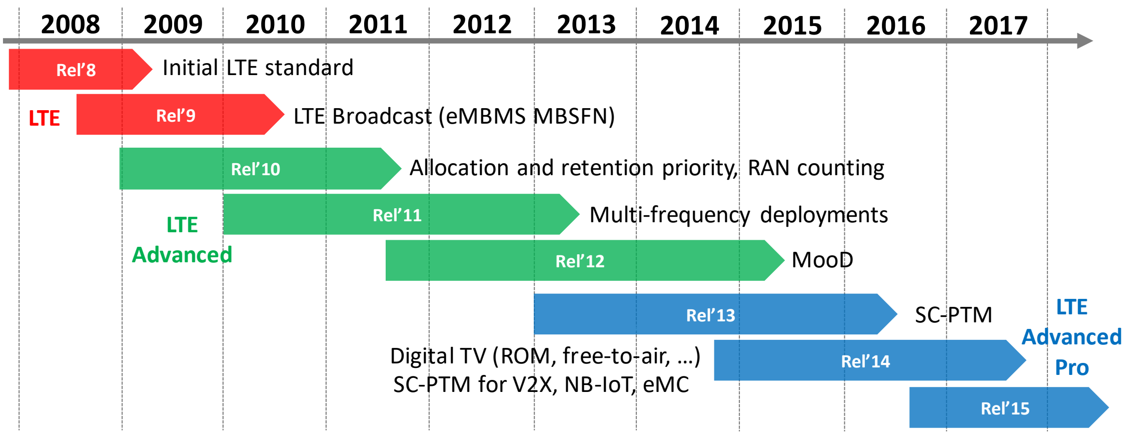

Figure 1: Point-to-Multipoint Evolution in 4G LTE. LTE-Advanced (Rel'10, '11 and '12) and LTE-Advanced Pro (Rel'13 and '14).

Rel'10 introduced a RAN-based counting of User Equipment (UEs) in connected mode interested in an MBMS service. This release also allowed the use of unused MBSFN subframes for unicast reception, and enhanced the admission control for MBMS sessions by the introduction of the allocation and retention priority session parameters.

Rel'11 introduced service acquisition and continuity in multi-frequency deployments where the MBMS service is provided via more than one frequency [3].

Rel'12 introduced as one of the main enhancements: MooD (MBMS operation on Demand), which enables automatic and seamless MBMS service activation and deactivation based on the UEs' service consumption reporting [4]. Rel'12 also introduced improvements in the physical measurements (e.g., signal power, error rates) the UEs can be ordered to perform for MBSFN network optimization, and specified eMBMS support for critical communications (in particular, as part of the group communication service enablers).

Rel'13 introduced SC-PTM (Single-Cell PTM) to increase the resource allocation flexibility for PTM [5]. SC-PTM allows one cell to broadcast the same content to a group of UEs, multiplexing broadcast and unicast data on the same physical downlink shared channel (PDSCH) instead of using the physical multicast channel (PMCH) that is a dedicated physical channel for broadcast. This allows a very flexible and dynamic radio resource allocation for broadcast transmissions, equivalent to unicast. Furthermore, it also benefits from a reduced end-to-end latency. SC-PTM could also exploit the unicast feedback for advanced link adaptation schemes such as adaptive modulation and coding for groups with a small number of UEs. However, this feature was finally not standardized in Rel'13. SC-PTM reuses eMBMS architecture and core network procedures and partially re-uses eMBMS procedures in RAN.

Rel'14 introduced MBSFN and SC-PTM for V2X (vehicular to everything) communications, SC-PTM for Internet of Things (IoT) solutions eMTC (enhanced Machine-Type Communication) and NB-IoT (NarrowBand-IoT). Rel'14 also introduced many features to enhance the delivery of TV services with eMBMS, to expand the reach of MBMS into traditional TV receivers and to enable the deployment of dedicated broadcast eMBMS networks supporting public broadcasting requirements [6]. Services provided may be distributed in such a way that they can be received by all, including those who are not mobile subscribers. This extends the applicability of mobile broadcast to support public broadcasting requirements.

1.2 Evolution of the 5G-Xcast verticals in the 3GPP

1.2.1 M&E vertical evolution

The main progress for the 5G-Xcast Media & Entertainment (M&E) vertical for television broadcasting has been produced within the EnTV (Enhancements for Television Service) work item in Rel'14. 3GPP has naturally updated the service layer to support new features (e.g., Dynamic Adaptive Streaming over HTTP DASH) and codecs (e.g., HEVC H.265) over the different releases that are relevant for the M&E vertical in general. However, those enhancements are not considered here.

Radio access enhancements of eMBMS in Rel'14 include dedicated carriers with up to 100% MBMS allocation and self-contained system information and synchronisation signals (including a new type of MBSFN subframe without unicast control region to reduce the signalling overhead). A 200 µs long cyclic prefix to support large inter-site distances has also been included. It should be noted that these improvements are not backwards compatible with previous releases, meaning that pre-Rel'14 UEs cannot receive any service from cells operating with these improvements. Hence they are only suitable for new Rel'14 deployments.

Architecture enhancements of eMBMS in Rel'14 include new device modes, such as the receive only mode (ROM) for devices without SIM card or 3GPP subscription; new service types to enable free-to-air content broadcast that can be received by all, including devices without subscription, as well as interactive services with ROM devices; an open standardized broadcasting application programming (xMB) external interface towards the TV content providers; transport-only (pass-through) MBMS bearer service type to use the eMBMS network as content delivery platform in the native format without transcoding; and shared networks among several MNOs (mobile network operators) to avoid broadcasting the same content at the same time over different networks and improve the radio resource utilisation.

The combination of receive only mode devices and shared MBMS architecture enables the deployment of standalone eMBMS broadcast networks. Figure 2 shows a simplified eMBMS architecture for TV services with a new MBMS Application Programming Interface (MBMS-API) that has been introduced to simplify access to complex eMBMS procedures.

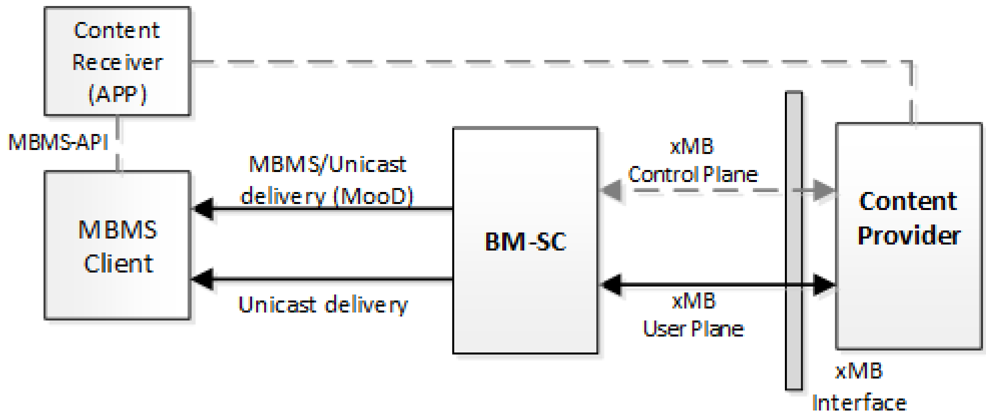

Figure 2: Simplified architecture for TV services over 3GPP eMBMS Rel'14.

1.2.2 PW vertical evolution

Public Warning (PW) is specified by 3GPP in 3GPP TS 22.268, Public Warning System (PWS) Requirements. This specification was written in the 3GPP Rel'8 timeframe specifically for the Japanese Earthquake and Tsunami Warning System. In Rel'9 CMAS (commercial mobile alerts) was added. After this happened the specification was generalized to PWS, which now has four regional variants:

1. ETWS (Earthquake and Tsunami Warning System
2. CMAS (now called WEA (Wireless Emergency Alert))
3. EU-Alert (specified in ETSI TS 102 900)
4. Korean Public Alert System (KPAS)

ETWS consists of a primary notification, which allows delivering a warning message within 4 seconds, and a secondary notification. The ETWS secondary notification and the CMAS, EU-Alert and KPAS messages are quite similar, but CMAS, EU-Alert and KPAS are fully compatible services.

The stage 2 specification for PWS is 3GPP TS 23.041, Cell Broadcast Service Specification. PWS is a text based warning service which allows broadcasting of text messages to all UEs in a specific area.

The last major addition to 3GPP TS 23.041 in the Rel'12 and Rel'13 timeframe was the addition of PWS support in E-UTRAN.

PWS is a mandatory service in 5G and is being specified in 3GPP CT (core network and terminal) WG1 (working group 1) and the update of 3GPP TS 23.041 should be finished in June 2018.

The FCC (Federal Communications Commission) has published the Report and Order FCC 16-127 on September 29, 2016 in which the section on Further Notice of Proposed Rulemaking discusses the FCC's position that the general public should benefit from multimedia content in WEA. 3GPP has not allocated priority to MBMS in Rel'15, the 5G phase-1 release. Discussions on priority for Rel'16 will take place after mid-2018 and not earlier due to a time-budget shortage in the RAN groups.

1.2.3 Automotive vertical evolution

To extend the LTE platform to new service verticals, as well as to meet the currently undergoing key technological transformations of the automotive industry, study items have been carried out by 3GPP on the use of LTE mobile networks in automotive use cases to ensure connectivity between vehicles/devices, the people inside/around the connected vehicles/devices and roadside infrastructure, leading to the study on service aspects for LTE-based Vehicle-to-Everything (V2X), where the usefulness of new LTE features to the automotive industry, including Proximity Service and LTE-based broadcast services such as PWS and eMBMS, have been particularly focused.

More specifically, vehicle-to-vehicle communications have been proposed based on device-to-device communications defined as part of proximity services in Rel'12 [7] and Rel'13 of the specification [8]. As part of proximity services, the device-to-device communication system interface that designated as sidelink at the physical layer, i.e., PC5, was introduced and now as part of the Vehicle-to-Vehicle Work Items, and it has been enhanced for vehicular use cases, particularly focusing on the solutions for high speed, e.g., up to 250Kph and high density, e.g., thousands of nodes.

To continuously developing functionality to provide enhancements specifically for vehicular communications both in terms of direct communication and for cellular communications with networks, the initial Cellular V2X standard, for inclusion in the Rel'14, was completed September 2016 during the 3GPP RAN meeting in New Orleans. It focuses on vehicle-to-vehicle communications, with further enhancements to support additional V2X operational scenarios to follow in Rel'14. In March 2017, the European Telecommunications Standards Institute (ETSI) released the first completed version of technical specification providing 3GPP supports for V2X service requirements to be supported by LTE transport [9]. The requirements of safety and non-safety aspects are included in [9], where the specific service requirements, e.g., latency/reliability, speed, service range, frequency and message size, as well as security requirements are specified.

Currently in Rel'15, the support of advanced V2X services, e.g., vehicle platooning, advanced/remote driving, extended sensors, that still being backward compatible with Rel'14 V2X for the delivery of safety messages, is covered[1]. The improvements have been taken into considerations for PC5 link, e.g., aggregation of up to 8 PC5 carriers under CA (Carrier Aggregation) feature, 64QAM (Quadrature Amplitude Modulation), transmit diversity and short TTI (Transmission Time Interval).

1.2.4 IoT vertical evolution

The IoT concept first appeared in Rel'12 [10], where the LTE Massive Type Communication (MTC) technology was introduced. This technology was designed to use LTE technology and frequency in-bands. In LTE MTC, the requirements were based on cost reduction and coverage improvement of 20 dB for low-cost MTC UEs in comparison to defined LTE cell coverage for normal UEs. Then, in Rel'13 this technology was improved and recalled as LTE eMTC, and a new UE category was defined (category M). The major improvements were: the reduction in the bandwidth to 1.08 MHz, the increase on the coverage range to 155.7 dB, and the reduction of cost and power with a long battery life (approximately 10 years of operation) with respect to the previous Rel'12

[1] https://www.grandmetric.com/2017/04/26/3gpp-release-15-further-lte-enhancements-and-5g-normative-work-kick-off/

technology. In addition to eMTC, two more technologies were added in Rel'13. The EC-GPRS (Extended Coverage GPRS) technology [11] designed to operate on GSM bands was introduced. Its objectives are the improvement of the coverage (to 164 dB with 33dBm power class or 154 dB with 23 dBm power class) and the power efficiency, the support of massive number of low throughput devices and a reduction of the complexity. The third IoT technology introduced in Rel'13 was NB-IoT. This technology has three operational options: in-band LTE carrier, LTE guard bands or standalone in re-farmed GSM spectrum. The goals of this technology are the reduction of the cost with respect to eMTC, extended coverage to 164 dB for standalone, the support to massive number of devices and a longer battery life (10 years).

During Rel'14, these technologies were further improved, with the main enhancement of the support of multicast (SC-PTM) for both eMTC and NB-IoT. In addition to this, the major enhancements with respect to the LTE eMTC were the higher data rates and the support for VoLTE (Voice over LTE). On the other side, with respect NB-IoT the major enhancements were the reduction on power consumption and latency. Finally, the EC-GSM technology main improvement during this Rel'14 was the extension on the coverage at least 3dB thanks to the improvement of the MCL (Maximum Coupling Loss).

Currently, in the Rel'15 [12] is addressed the data delivery from the network to a large amount of UEs using MBMS. The considered requirements are the support of: reliable delivery, the reports on successful delivery, eMBMS delivery mechanism and procedures for devices with limited capabilities (e.g. limited battery life of 15 years) and a mechanism to acknowledgment a successful reception.

1.3 5G development and PTM communications

3GPP started in March 2017 the normative work for 5G in Rel'15, also known as New Radio (NR), focusing on a PTP (point-to-point) network infrastructure solution and the early 5G deployments. 3GPP Rel'16 work will start in 2018 and it will target the ITU (International Telecommunications Union) IMT-2020 (International Mobile Telecommunication) submission. IMT-2020 systems are mobile systems that include new radio interface(s) to support new capability beyond those shown in IMT-200 and IMT-Advanced providing diverse services in the identified three usage scenarios: enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). The key requirements related to the minimum technical performance of IMT-2020 candidate radio technologies is published in [17] and the guidelines for the evaluation for a number of test environments is published in [18].

The 3GPP TS 22.261 (Service Requirements for the 5G system) [19] has identified, amongst other items, flexible broadcast/multicast service as a basic capability for the 5G system and sets out a list of potential requirements. Also, the study item TR 38.913 (Study on Scenarios and Requirements for Next Generation Access Technologies) [20] sets out MBMS requirements for NR. However, the support of broadcast and multicast capabilities is currently envisioned for evaluation in Rel'16 or Rel'17 due to the very tight schedule of 5G NR and the high workload of the 3GPP TS WG on Radio layer 1 (RAN1).

1.4 Objectives of the document

This document first aims to define technical requirements for the RAN derived from the six high-level use cases of four vertical sectors in D2.1 [21] encompassing Media & Entertainment (M&E), Public Warning (PW), Automotive (Auto), and Internet of Things (IoT).

The selection of the Key Performance Indicators (KPIs) and evaluation methodology for the RAN benchmark in WP3 (Work Package 3) is aligned with one defined by the ITU-R for the IMT-2020 radio interface technology (RIT) evaluation process [18]. The present document first has the goal to select the KPIs relevant for the use cases in the 5G-Xcast project taking into account both PTP and PTM transmission modes. Since the KPIs listed in [18] for the IMT-2020 RIT evaluations are mainly for PTP, additional KPIs together with its evaluation methodology are defined to better assess specific aspects in the performance of scenarios with PTM transmissions such as e.g., traditional TV broadcasting deployments.

The performance evaluation of the selected KPIs targets the recently standardised 3GPP Rel'14 LTE-Advanced-Pro specification for both PTP and PTM transmission modes since most of the relevant use cases in [21] use a combination unicast and multicast/broadcast components. For PTM the evaluation includes the state-of-the-art LTE eMBMS technologies, i.e., SC-PTM and MBSFN, taking into account the performance comparison between these technologies and the latest terrestrial broadcasting standard ATSC 3.0 (Advanced Television Systems Committee). The standardisation of the physical layer of ATSC 3.0 was completed in 2017 has been optimized over other terrestrial broadcasting standards [15], e.g., DVB-T2 (Digital Video Broadcasting – 2nd Generation Terrestrial), and is taken as state of the art DTT technology. The evaluations are performed, for the different KPIs, by analytical procedure, inspection procedure or by simulation procedure. In particular, link level, system level and coverage simulations investigate the performance for different transmission parameters and environments (e.g., dense urban, rural, indoor, mobile and fixed rooftop antenna). The selected environments are representative of the WP2 use cases and are also aligned to the test environments as defined in the IMT-2020 evaluation guidelines. These evaluations permit to provide a summary of the relevant KPI performance of current state-of-the-art technologies in the selected WP2 use cases.

Finally, this document has the objective to identify technical limitations of the LTE-Advanced-Pro Broadcast RAN for the air interface, radio access technology protocols and spectrum based on the investigations carried out. This permits to outline potential technologies, procedures and areas of research to overcome such limitations in the following tasks within the 5G-Xcast project is provided.

1.5 Structure of the document

This document is structured as follows. First, it describes in Chapter 2 the RAN technical requirements derived for WP3. Then, Chapter 3 identifies the limitations of LTE Rel'14 according to the studies conducted in this document. Chapter 4 provides the technical RAN benchmark of the technical KPIs. Finally, Chapter 5 summarises the findings of the investigations carried out and discusses the main areas of potential improvement towards the development of technical solutions in the subsequent tasks in the project.

2 5G-Xcast RAN Technical Requirements

Six high-level use cases of four vertical sectors encompassing Media & Entertainment (M&E), Public Warning (PW), Automotive (Auto), and Internet of Things (IoT), have been defined in WP2 D2.1 [21]. The use cases were intentionally high-level and broad in nature with the specification of detailed technical requirements and KPIs being carried out in the technical WPs, specifically WP3, WP4 and WP5. The use cases defined in D2.1 and their respective high-level requirements have been studied by WP3 and those having a direct impact on radio access aspects are identified below. For each one, the requirements or relevance to defining the solution in WP3 are highlighted.

No.	Use case M&E 1 – The Hybrid Broadcast Service
M&E1_R3	• Broadcast/multicast support required.

M&E1_R7	• Feedback mechanisms to optimize radio resource allocation
	  ○ Optimisation of choice of Modulation and Coding Scheme (MCS) for broadcast/multicast
	  ○ Optimisation of use of broadcast/multicast or unicast bearers
	• Support for broadcast/multicast and unicast for interactivity

M&E1_R10	• Concurrent reception of broadcast/multicast and unicast
M&E1_R14	• A range of cyclic prefixes to cover different scenarios in rural, sub-urban and urban areas
M&E1_R15	• Broadcast/multicast will fulfil user density requirements but design of unicast radio access technology will need to take this into account
M&E1_R16	• Broadcast/multicast will fulfil concurrent user requirements but design of unicast radio access technology will need to take this into account
M&E1_R17	• Should focus on coverage to outdoor, indoor and to vehicles.
M&E1_R18	• Should fulfil all mobility classes defined in IMT-2020, including speeds of 250 km/h
M&E1_R20	• End-to-end (i.e. from content service provider to end user) transport layer security of multicast traffic must be equivalent to that of unicast traffic.
M&E1_R23	• Video bit-rates for UHD (Ultra High Definition) are higher than for HD (High Definition). Therefore, the RAT (Radio Access Technology) should target delivery of UHD content within the same resources as HD today through the use of, e.g. higher order constellations, improved error coding, time interleaving, MIMO (Multiple-Input and Multiple-Output) or better frequency re-use within the network.
M&E1_R24	• End-to-end latency is not highly critical in this use case. However, design of any time interleaving mechanism shall ensure that channel change latency is less than 1 second.
M&E1_R25	• Quasi-error free reception implies 1 uncorrected error per hour. In the case of a 50 Mbit/s stream, equating to a target BER (Bit Error Rate) of approximately 5^{-12} for broadcast/multicast. Note that in the case of unicast, re-transmission mechanisms may be used to achieve this.
M&E1_R28	• Support for delivery of regional content, i.e. different transmitter may deliver different content removing the possibility to always use large-scale single frequency networks.

No.	Use case M&E 1 – The Hybrid Broadcast Service
M&E1_R29	• Spectral efficiency for the PTM should be at least as good as current state-of-the-art systems.
M&E1_R30	• The system shall be flexible to support different network topologies including existing High Power High Tower and Low Power Low Tower deployments.
M&E1_R31	• The system should be as flexible as possible regarding which frequency bands it supports.
M&E1_R33	• Support an uplink channel for audience metrics and service performance monitoring.
M&E1_R34	• The 5G-Xcast solution should be designed in a way as to minimise the need for excessive updates to the hardware capabilities of consumer equipment, including UEs o There is opportunity to take advantage of capabilities used for unicast but not currently used for broadcast such as multiple antennas.
M&E1_R36	• The radio access networks in 5G-Xcast system should maximize the system's spectral efficiency when unicast and multicast/broadcast services are deployed in the same frequency.

No.	Use case M&E 2 – Virtual/augmented reality broadcast
M&E2_R1	• For fully immersive VR (Virtual Reality) content delivery at 5 Gbit/s, techniques such as mmWave, carrier aggregation and MIMO could be examined.
M&E2_R2	• To achieve the low latency requirement for unicast the latest developments such as URLLC should be considered and for broadcast/multicast constraints on time interleaving depths and feedback techniques should be considered
M&E2_R3	• Broadcast/multicast will fulfil user density requirements but design of unicast radio access technology will need to take this into account.

No.	Use case M&E 3 – Remote live production
M&E3_R1	• For mezzanine quality (e.g. 100 Mbit/s) and uncompressed (e.g. 9 Gbit/s) video content, techniques such as mmWave, carrier aggregation and MIMO could be examined.
M&E3_R2	• To achieve the low latency requirement for unicast the latest developments such as URLLC should be considered and for broadcast/multicast constraints on time interleaving depths and feedback techniques should be considered.
M&E3_R3	• A very high quality of service delivery is required with a target BER of $<10^{-11}$.
M&E_R4	• Should fulfil the stationary mobility class defined in IMT-2020.

No.	Use case PW 1 – Multimedia public warning alert
PW1_R4	• Transmission of messages targeted to groups of users with a cell level granularity.

No.	Use case PW 1 – Multimedia public warning alert
PW1_R5	• The RAN should be designed such that receiver algorithms do not dramatically decrease battery life compared to current state of the art and the frame structure so designed so as to allow a receiver to sleep efficiently.
PW1_R12	• For very high priority alerts, the RAN solution should ensure a very low probability of failure to deliver the message to the receiver over broadcast/multicast and be comparable with the reliability of existing public warning solutions and to unicast delivery.

No.	Use case Auto 1 – V2X broadcast service
Auto1_R1	• To achieve the low latency requirement for unicast the latest developments such as URLLC should be considered and for broadcast/multicast constraints on time interleaving depths and feedback techniques should be considered.
Auto1_R2	• A high quality of service delivery is required with a target packet loss rate of $<10^{-5}$.
Auto1_R3	• Broadcast/multicast will fulfil user density requirements but design of unicast radio access technology will need to take this into account.

No.	Use case IoT 1 – Massive Software Updates
IoT1_R1	• The RAN should be designed such that receiver algorithms do not dramatically decrease battery life compared to current state of the art and the frame structure so designed so as to allow a receiver to sleep efficiently.
IoT1_R2	• Support an uplink channel for successful delivery reports.
IoT1_R3	• The RAN frame structure should be designed so as to allow a receiver to sleep efficiently.
IoT1_R4	• Broadcast/multicast will fulfil user density requirements but design of unicast radio access technology will need to take this into account.
IoT1_R5	• The system should allow coverage extension capability. (Note: this requirement is not included in D2.1 but is presented here due to its relevance).

3 Limitations of LTE-Advanced Pro Broadcast Radio Access Network

3.1 Limitations on Air Interface

The following list presents the identified limitations on the air interface of LTE Advanced Pro broadcast access network in task T3.1, which have been group into families:

No.	Limitations on waveform flexibility and synchronization robustness
1	**Numerology options**: LTE MBSFN and SC-PTM are characterized by rigid OFDM (Orthogonal Frequency Division Multiplexing) numerology parameters that limit the type of network deployments. In LTE Rel'14 the MBSFN physical layer can be configured with CP (Cyclic Prefix) lengths of 16.7 μs, 33.3 μs and 200 μs. Even though the inclusion of 200 μs allows for significantly larger cell area deployments, OFDM numerology options are still limited compared with DTT (Digital Terrestrial Television) standards. For example, the DVB-T2 specification can allow large area SFN (Single Frequency Networks) deployments for fixed rooftop antennas with a CP of 448 μs, which is significantly higher than that currently allowed with 3GPP Rel'14.
2	**Synchronization in Receive Only Mode: Cell Acquisition Subframe:** In MBSFN, Cell Acquisition Subframes (CAS) carry signaling for Receive Only Mode. The CAS is configured with unicast numerology (15 kHz) and is non-SFN, which can limit the SFN coverage area. As it is shown in the performance evaluation in Section 4.3.3.2.1, the performance with the CAS suffers in interference-limited scenarios with large area network deployments.
3	**High mobility in large area deployments**: The introduction of a CP length of 200 μs (1.25 kHz subcarrier spacing) in Rel'14 MBSFN allows for larger cell deployments. However, during the standardization of larger CP lengths within Rel'14, RAN1 link level evaluations showed that the maximum speed for the case with larger CP was quite limited and around 100 km/h and this was also confirmed with the numerical evaluations performed in this report. Higher speeds are allowed with the shorter CP options; however these would need significantly denser network deployments.
4	**Coverage area adaptation and extension:** • The MBSFN area is statically configured regardless of user distribution; • it is not possible to dynamically create SFN on a cell level basis; and • it is not possible to use PTP, single cell PTM and multiple cell (SFN) PTM in different areas of the network to deliver the same service.

No.	Limitations on radio resource management
1	**Local/Regional coverage provision:** • local/Regional services can only be inserted by establishing different MBSFN Service Areas with TDM (Time Division Multiplexing); and • MBSFN is inefficient for cell-area broadcasting since it cannot be configured using MIMO, a short CP and reduced pilot signal overhead.
2	**Resource allocation:** • MBSFN resource allocation is static and it cannot adapt to the network traffic load. Subframes reserved for MBSFN operation are transmitted regardless of the user demand. To overcome this limitation, LTE Rel'14 allowed mapping of unicast data over the MBSFN subframes in the case that there is no broadcast content available, however only devices implementing Transmission Mode TM-9/10 are able to decode this data.

No.	Limitations on radio resource management
3	**Lack of feedback channel:** • The possibility to feedback channel state information to the eNodeB (eNB) about the MBSFN reception for users with uplink capabilities can be useful to perform link adaptation techniques for a group of users. This feature can be especially interesting for deployments with small cells with a limited number of users demanding the same content. In the case of receive only mode receivers with large cells, this feature is less relevant. • Retransmissions or channel state indicator feedback is not possible for SC-PTM since the MBMS bearer in the core network used for media delivery is defined as a RLC-UM (Radio Link Control-Unacknowledged Mode). This means that techniques like HARQ/ARQ (Hybrid Automatic Repeat Request), AMC (Adaptive Modulation and Coding) or Closed-Loop MIMO cannot be used for SC-PTM. 3GPP standardization studied the potential benefits of link adaptation techniques with uplink in SC-PTM and this showed potential benefits when the number of users is small [5].
4	**Unicast/Broadcast multiplexing:** • MBSFN subframes occupy the entire bandwidth. Multiplexing with unicast transmission in the frequency domain is not allowed (this could be solved in 5G PTP). TDM is the only multiplexing mechanism allowed in MBSFN. • The allocation of resources to broadcast in mixed unicast/broadcast multiplexing can be configured between 0% and 80% with steps of 2.5%. Note that Rel'14 has included a downlink only mode where 100% of the sub-frames are allocated to broadcast. In Rel'14, resource allocations to broadcast in increments between 80% and 100% is not supported. In the 100% broadcast allocation case, it is still required to transmit CAS that uses 1 subframe every 40 subframes, reducing the broadcast capacity to 97.5% of the total available resources. • Allocation for 60% to 100% requires a secondary cell that carries unicast data.

No.	Limitations on signal diversity techniques
1	**Frequency and Time Diversity:** MBSFN and SC-PTM lack frequency interleaving and time interleaving which could significantly improve the reliability of transmission for the receive-only mode that in itself lacks link adaptation techniques due to the uplink channel not being available.
2	**Statistical Multiplexing**: Statistical multiplexing in MBSFN and SC-PTM cannot be implemented up to and including Rel'14.
3	**Single Frequency Network Operation in SC-PTM**: SC-PTM cannot be configured in a SFN operation mode that can be beneficial when multiple cells are transmitting the same content.

No.	Limitations on spatial multiplexing and peak spectral efficiency
1	**Spatial Multiplexing:** MIMO techniques that provide spatial multiplexing gain are not defined for MBSFN in Rel'14.
2	**Peak spectral efficiency:** The maximum constellation size currently supported is 256QAM (Quadrature Amplitude Modulation). State-of-the-art DTT systems such as ATSC 3.0 allows larger constellations sizes up to 4096 constellation points per transmit antenna.

3.2 Limitations on Radio Access Technology Protocols

The following limitations have been identified after the study of eMBMS RAT protocols:

No.	Limitations on radio resource management
1	**Lack of resource allocation:** • Up to Rel'14, only up to 60% of subframes could be allocated to MBSFN services. Rel-14 added the option of using 2 additional subframes or the possibility of using all subframes for MBSFN, going up to 80% and 100% of resources allocated to the MBSFN services respectively. • For SC-PTM, the mapping of downlink physical channels and signals to physical resources as defined in Rel-13 has a limitation in that the number of OFDM symbols used for carrying the control channel (as signaled by the Control Format Indicator, CFI) is fixed at 3 for 5 MHz and lower bandwidths, or 2 for 10 MHz and higher bandwidths.
2	**Lack of feedback channel:** • There is no feedback from the radio access network to the core MBMS entities about the successful establishment of radio access bearers associated with a certain service. • For both MBSFN and SC-PTM, no retransmissions are allowed for the Multicast Traffic Channel (MTCH)/SC-MTCH, since it is defined as RLC-UM. • There is no dedicated feedback for SC-PTM link adaptation. The RAN implementation could use the feedback mechanisms defined for unicast transmission in proprietary SC-PTM link adaptation solutions but this is not optimal.

No.	Limitations on latency
1	• Control plane requires about 5 s to setup an MBSFN radio bearer, due to the long Multicast Control Channel (MCCH) modification period. Until Rel-14 modification periods were 5.12 s or 10.24 s. In Rel-14 the protocols included fast reconfigurations, still require modification periods of 10 ms. • MBSFN area configuration and available MBMS services have to be sent on MCCH periodically requiring an MCCH repetition period, which can be 320 ms and greater up to 2.56 s. With the fast reconfiguration in Rel'14, the repetition period is at least of 10 ms. • For SC-PTM, modifications have to be first announced in one modification period and actually signaled in the next modification period. Modification period can be one radio frame in Rel-14, and up to 2, 4, 8, ..., 256, ... 65536 radio frames in Rel'13. In addition, the offered MBMS services have to be sent on SC-MCCH periodically, where the repetition period is 1 radio frame in Rel-14, and 2, 4, 8, ..., 256 radio frames in Rel-13. • For MBSFN, the user plane requires a minimum delay of 40 ms (long multicast transport channel scheduling period,) for mixed unicast/broadcast transmission. • For SC-PTM, scheduling information for each service (i.e., each SC-MTCH) is provided in the system information. The UE attempts to receive SC-MTCH continuously or according to the discontinuous reception configuration.

No.	Limitations on service scheduling
1	**Service continuity:** • Service continuity is limited in MBSFN to the MBSFN service area. • To keep the service continuity in SC-PTM the UE is allowed to switch to unicast in a case of a handover and the new serving cell not transmitting a SC-PTM transmission. This feature is relevant for Mission Critical Services, where the degree of reliability of the service must be maintained.
2	**UE interest indication:** • In order to know, from the network side, the UE interest in a specific service, UEs have to indicate such interest via an "MBMS interest indication" Radio Resource Control (RRC) message in several cases including upon successful connection establishment, upon entering or leaving the service area, upon session start or stop, upon change of interest, upon change of priority between MBMS reception and unicast reception or upon a change to a PCell broadcasting. For MBSFN, the MCE (Multi-cell/multicast Coordination Entity) can use the MBMS counting procedure to count the number of RRC_CONNECTED mode UEs which are receiving via an MRB (Multi-behaviour and Reliable Broadcast) or interested to receive via an MRB the specified MBMS services.
3	**Inflexible control information acquisition:** • In order to save UE battery power in monitoring for the available of an MBMS broadcast, a trigger must come from the network side to wake up the MBMS reception. • The control plane and the indication of control information change is shared by all MBMS services within an MBSFN area or cell. This may have negative impacts on many aspects of the system and the UE performance when multiple services with various latency requirements use MBMS in the same MBSFN area or the same cell. For example, a UE interested in an MBMS service allowing for longer latencies must monitor for the control information change more frequently than necessary resulting in battery drain. It may not be necessary to specify a specific/explicit trigger mechanism for broadcast control information acquisition in 5G but if may be sufficient to include an MBMS notification in the paging message.

3.3 Limitations on Spectrum

The following list presents the identified limitations on spectrum of LTE Advanced Pro broadcast access network in task T3.1.

<table>
<tr><th colspan="2">Effective bandwidth limited to 90% of nominal channel bandwidth</th></tr>
<tr><td>1</td><td>3GPP standardizes six bandwidth values: 1.4, 3, 5, 10, 15, and 20 MHz, with OFDMA (Orthogonal Frequency Division Multiple Access) multiplexing scheme in the downlink. A series of null carriers are used to reduce OOBE (Out of Band Emissions) resulting in the bandwidth efficiencies shown in Table 1. Thus, the maximum possible transmission bandwidth per carrier is 18 MHz.

Table 1: Bandwidth efficiencies in LTE
<table>
<tr><td>Channel BW (MHz)</td><td>1.4</td><td>3</td><td>5</td><td>10</td><td>15</td><td>20</td></tr>
<tr><td>Transmission BW (MHz)</td><td>1.08</td><td>2.7</td><td>4.</td><td>9</td><td>13.5</td><td>18</td></tr>
<tr><td>BW Efficiency (%)</td><td>77.1</td><td>90</td><td>90</td><td>90</td><td>90</td><td>90</td></tr>
</table></td></tr>
<tr><th colspan="2">Carrier Aggregation (CA) limited to 5 Component Carriers (CC)</th></tr>
<tr><td>2</td><td>Carrier Aggregation (CA) is used to increase the bandwidth (and peak data rate) by the bonding of multiple carriers. Each aggregated carrier is referred to as a Component Carrier (CC) and a maximum of 5 CCs can be aggregated leading to a maximum CA bandwidth of 100 MHz (i.e., 90 MHz maximum transmission bandwidth).</td></tr>
<tr><th colspan="2">MBSFN Operation in Adjacent Areas</th></tr>
<tr><td>3</td><td>SFN is supported via MBSFN subframes in which time-synchronized signals with common waveform parameters are transmitted from different stations. UEs within the SFN area can benefit from transmitter diversity and reduced interference (as long as the relative delay between received signals do not exceed the Cyclic Prefix duration).
3GPP TS 36.300 [13] and TR 36.868 [14] define the concepts of MBSFN Area and MBMS Service Area: An MBMS Service Area defines the geographic area where the operator decides to broadcast a determined service. This region can be divided into several MBSFN Areas. An MBSFN Area defines the group of cells which provide the same SFN service. Different MBSFN Areas can overlap and coexist but each MBSFN Area should transmit in a different time slot to avoid interferences which leads to spectrum reuse in the time domain. In order to further reduce the inter-cell interference, a set of reserved cells (see Figure 3) around the MBSFN area can be deployed, in which there is no transmission of the PMCH (Physical Multicast Channel) during active MBSFN subframes.


Figure 3: Example of MBSFN network with a ring of Reserved Cells to prevent interference from adjacent MBSFN Areas. The PMCH is not transmitted so that the reserved cells do not contribute to the SFN</td></tr>
</table>

4 RAN Benchmark of Technical KPIs

4.1 Introduction

WP3 has used as reference for the RAN benchmark the KPIs and evaluation methodology defined by the ITU-R for the IMT-2020 RIT evaluation process [18] . It should be pointed out that the IMT-2020 RIT is assumed to be a PTP-only solution but has been used as the basis for the evaluation of PTM in the context of 5G-Xcast.

The IMT-2020 RIT evaluation process defines the technical performance requirements for three usage scenarios namely eMBB, URLLC and mMTC, and their corresponding evaluation methodology [17]. There are three evaluation procedures:

- **Simulation procedure**: including system-level, link-level and coverage simulations. This method is applied for KPIs that are heavily dependent on the instantaneous network conditions, such as available infrastructure, radio resources, number of users, radio conditions, etc.
- **Analytical procedure**: via mathematical analysis. The evaluation is based on calculations that use technical information.
- **Inspection procedure**: by reviewing the functionality and parameterization of the proposal. This method is applied to KPIs that are design-dependent and can be assessed by looking into general system design information.

Table 2 presents the summary of the high-level assessment method used per KPI, following the evaluation methodology described in [18]. WP3 has adopted a subset of the KPIs of the IMT-2020 process for the evaluation of PTM wireless solutions and it is these that will be used for the evaluation of the 5G-Xcast RAN.

Table 2: High-level assessment method used per KPI in IMT-2020. Adoption in WP3, usage in D3.1 and relevance to PTM are also shown.

KPI for evaluation	Scenario	Assessment method	Adopted in WP3	Evaluated in D3.1	PTM
Bandwidth	eMBB, mMTC, URLLC	Inspection	X	X	X
Energy efficiency	eMBB, mMTC	Inspection	X		X
Peak data rate	eMBB	Analytical	X	X	X
Peak spectral efficiency	eMBB	Analytical	X	X	X
User plane latency	eMBB, URLLC	Analytical	X		X
Control plane latency	eMBB, URLLC	Analytical	X		X
Mobility	eMBB, URLLC	Link Level Simulation	X	X	X
Average spectral efficiency	eMBB	System Level Simulation	X	X	
5th percentile User spectral efficiency	eMBB	System Level Simulation	X	X	
Reliability	URLLC	System Level Simulation	X		

Latency, energy efficiency and reliability KPIs have not been evaluated in D3.1. It is expected that ITU-R will approve the IMT-2020 evaluation methodologies in the next meeting in November 2017. At this point the report in [18] will no longer be a draft.

WP3 has also defined three additional KPIs to better assess the overall performance of PTM transmissions as shown in Table 3. The selected KPIs are BICM (Bit-Interleaved Coded Modulation) spectral efficiency, peak BICM spectral efficiency and coverage. These KPIs are directly related to broadcast, with some of them directly adapted from PTP. The KPIs defined below have been widely used in the standardization for digital terrestrial television systems.

Table 3: Additional KPIs adopted by WP3.

KPI for evaluation	Scenario	Assessment method	Adopted in WP3	Evaluated in D3.1	PTM
BICM spectral efficiency	eMBB, URLLC, mMTC	Link Level Simulation	X	X	X
Peak BICM spectral efficiency	eMBB	Analytical	X	X	X
Coverage	eMBB URLLC, mMTC	Coverage Simulation	X	X	X

4.2 KPIs Description

4.2.1 Generic PTP and PTM KPIs

- **Bandwidth** (Hz): maximum aggregated system bandwidth in Hz (including frequency guard bands). The maximum supported bandwidth may be composed of either a single or multiple radio frequency (RF) carriers.
- **Peak spectral efficiency** (bit/s/Hz): maximum data rate normalised by carrier bandwidth when excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times.
- **Peak data rate** (bit/s): peak spectral efficiency multiplied by the maximum bandwidth supported by the system.
- **BICM spectral efficiency** (bits/channel use or bits/symbol) indicates the number of data bits per channel used. The BICM spectral efficiency depends on the received carrier-to-noise ratio (CNR). In LTE systems a channel use is a Resource Element (RE) (defined as one subcarrier of one OFDM symbol). In the CNR definition used in this deliverable, the carrier power refers to information carrier power or the power in the REs in LTE systems. The BICM spectral efficiency is calculated as the number of useful data bits carried in a single RE multiplied by the channel code-rate (e.g., a transmit configuration with QPSK (Quadrature Phase Shift Keying) constellation and a channel code-rate of 1/2 has a BICM spectral efficiency of 1 bits/symbol) that can be decoded at a received CNR. This calculation only focuses on data RE, i.e. it does not take into account the spectral efficiency of control symbols.
- **Peak BICM spectral efficiency** (bits/channel use or bits/symbol): maximum BICM spectral efficiency supported by the system assuming ideal reception conditions (i.e., it does not depend on the received CNR). This calculation can include the use of multiple spatial streams (antenna ports) if the system supports multi-antenna transmissions.
- **Coverage** (% of population covered): defines the spectral efficiency (or data rate) available in a geographical area with certain probability. Due to lack of feedback

mechanisms in broadcast networks, link adaptation techniques that adapt the transmission data rate to the user quality conditions cannot be used. Hence, in broadcast systems, services are planned to cover a particular physical area with a target probability that a given SINR (Signal-to-Interference plus Noise Ratio) within the area is achieved. Reference [22] provides a three-level approach to define the coverage in a given reception scenario, see Figure 4:

- Receiving location: The smallest unit is a receiving location with dimensions of about 0.5 m × 0.5 m. Such a location is regarded as covered if the required carrier-to-noise and carrier-to-interference values are achieved for 99% of the time.
- Small area coverage: In a "small area" (typically 100 m × 100 m) the percentage of covered receiving locations is calculated. The coverage of a small area is classified as:
  - "Good", if at least 95% of receiving locations within the area are covered for portable reception and 99% of receiving locations within it are covered for mobile reception.
  - "Acceptable", if at least 70% of receiving locations within the area are covered for portable reception and 90% of receiving locations within it are covered for mobile reception.
- Coverage area: The coverage area of a transmitter, or a group of transmitters, is made up of the sum of the individual small areas in which a given class of coverage is achieved:

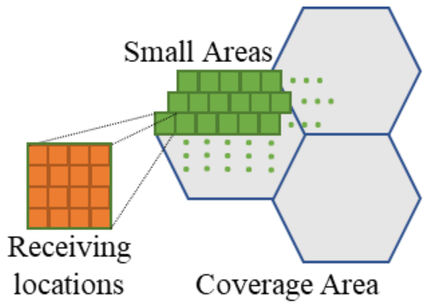

Figure 4: Three-level approach for the definition of the coverage: Receiving locations, Small area coverage and Coverage area.

- **Mobility** (km/h): the maximum speed of a user equipment at which a defined quality of service (QoS) can be achieved. The following classes of mobility are defined in D2.1 [21]:
  - Stationary: 0 km/h.
  - Pedestrian: 0 to 10 km/h.
  - Vehicular: 10 to 120 km/h.
  - High speed vehicular: 120 to 500 km/h.

Note that in the MBMS requirements for NR in [20] the mobility requirement is set to 250 km/h. 5G-Xcast will set the same requirement for PTM transmissions as the requirement imposed to PTP transmissions for this KPI.

4.2.2 PTP Specific KPIs

- **User spectral efficiency** (bit/s/Hz): User spectral efficiency (during active time) is defined as the number of correctly received bits per second divided by the total carrier bandwidth.[2] A cumulative distribution function (CDF) of the user spectral efficiency is collected over all possible user locations. The mean and the 5th percentile of this CDF are of particular interest defining the average and "cell-edge" user data rates.

- **Average Cell spectral efficiency** (bit/s/Hz/TRxP): aggregated throughput of all users divided by the total number of users, divided by the total used bandwidth of the shared communication channel and divided by the number of Transmission Reception Points (TRxPs).

4.2.3 KPIs not considered in D3.1

- **Reliability**: capability of transmitting a given amount of traffic within a predetermined time duration with a high success probability. More precisely, this KPI is the success probability of transmitting a layer 2/3 packet within a required maximum time, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU (Service Data Unit) egress point of the radio interface at a certain channel quality.
- **Energy efficiency** (bits/Joule): capability of a radio interface technology to minimize the radio access network energy consumption in relation to the traffic capacity provided. [23] divides the energy efficiency into two aspects: on the network side, where the energy efficiency is defined as the quantity of information bits transmitted/received from users per unit of energy consumption of the RAN, and, on the other hand on the device side, where it is defined as the quantity of information bits per unit of energy consumption of the communication module.
  In both cases, as specified in [17], the energy efficiency is related to:
  - the support of an efficient data transmission in a loaded case, and;
  - a low energy consumption when there is no data transmission.

  Efficient data transmissions are demonstrated by the average spectral efficiency. A low energy consumption when there is no data can be estimated by the sleep ratio. The sleep ratio is defined in [17] depending on the network/device point of view as:

  - Network: the fraction of unoccupied time resources in a period of time corresponding to the cycle of the control signalling.
  - Device: sleeping time in a period of time corresponding to the cycle of discontinuous reception, when no user data transfer takes place.

  Furthermore, the sleep duration, i.e. the continuous period of time with no transmission (for network and device) and reception (for the device), should be sufficiently long. Note that this requirement is defined for evaluation in eMBB scenarios, but it can be extrapolated to PTM transmissions, since energy efficiency conditions are very similar in broadcasting scenarios. The network shall have the capability to support a high sleep ratio and long sleep duration.

- Latency: The latency performance of a system can be evaluated for either user plane latency or control plane latency or both, where
  - **User plane latency** (ms): the contribution of the radio network to the time from when the source sends a packet to when the destination receives it. User plane latency is defined in [17] as the one-way transit time between a packet being available at the IP (Internet Protocol) layer in either the UE/RAN edge node and

[2] Note that there is an alternative definition, where the transmitted data rate is normalized by the bandwidth actually allocated to the corresponding transmissions. This alternative definition does not account for the fact that a user may only get a share of resources in a shared channel like the PDSCH or PUSCH in LTE.

the availability of this packet at IP layer in the RAN edge node/UE. The RAN edge node is the node providing the RAN interface towards the core network.

- **Control plane latency** (ms): time from a “battery efficient” state (e.g. idle state) to the start of continuous data transfer (e.g. active state).

4.3 KPIs Evaluation Methodology

The methodology in this deliverable is structured around the different evaluation types considered, i.e. analytical, link-level simulations, coverage simulations and system-level simulations. This section explains the different methodologies followed in D3.1.

4.3.1 Inspection Evaluation

4.3.1.1 Bandwidth

The maximum aggregated system bandwidth is calculated by inspection taking into account the total bandwidth that may be supported by multiple RF carriers.

4.3.1.2 Energy efficiency

The energy efficiency evaluation methodology defined by [18] for both network and device is verified by inspection, demonstrating that the candidate RITs/SRITs can support high sleep ratio and long sleep duration when there is no data.

From the mMTC point of view, energy efficiency has been studied by 3GPP in [24] where the purpose was to calculate the battery life for an MTC device when using a specific candidate solution. This requirement may depend on the traffic and coverage needs of specific users. Poorer channel conditions and higher power demands will naturally increase the power consumption and therefore reduce battery life.

3GPP TR 36.888 [25] describes the methodology of measuring power consumption with dependence on many factors such as active transmission time, transmit power level, sleep mode duration, active reception time, or receiver processing time/complexity. As reference [25] mentions, some factors, like sleep mode duration, may depend on network configuration and traffic/signalling patterns, and some other factors, such as efficiency and receiver processing may be implementation specific. Reference [25] also states that UE power consumption of the RF module can be estimated by:

- reception time;
- transmission time and total UE transmit power during the transmitting time;
- DC (Direct Current) power consumption of power amplifier efficiency.

Power estimation for most baseband integrated circuits is usually calculated by commercial power estimation tools. In order to obtain the baseband power consumption conveniently, it is recommended to use a baseband complexity evaluation or comparison.

4.3.2 Analytical Evaluation

4.3.2.1 Peak data rate

For LTE, the peak data rate KPI is calculated as:

$$Rate_p = \frac{TBS_{max}}{T_{subframe}},$$

where TBS_{max} is the maximum transport block size in bits delivered every TTI, and $T_{subframe}$ is the subframe duration in seconds. Note that the transport block size changes with the number of antennas, and therefore MIMO configurations are also included in this calculation.

For ATSC 3.0, it is calculated considering the different system parameters, i.e. FEC (Forward Error Correction) code rate, modulation order, FFT (Fast Fourier Transform) size, pilots overhead, CP length, L1-basic, L1-detail, bootstrap symbols and frame duration.

$$Rate_p = \frac{Net_{Bits}}{T_{frame}},$$

where Net_{Bits} is the maximum number of net bits that are transmitted in one frame, calculated as follows:

$$Net_{Bits} = FEC_{Blocks} \cdot CR_T,$$

with CR_T as the FEC coding rate taking into account the outer and inner codes, and FEC_{Blocks} as the maximum number of FEC blocks that can be transmitted in a frame rounded down, considering the number of data cells and the modulation. It can be calculated as:

$$FEC_{Blocks} = \left\lfloor \frac{DataCells_{frame} \cdot \log_2 m_{max}}{FEC\ length} \right\rfloor$$

Note that $DataCells_{frame}$ is obtained considering the different overhead of the system (bootstrap and preamble symbols, pilot overheads, CP length and guard bands).

4.3.2.2 Peak spectral efficiency

For both LTE and ATSC 3.0 the peak spectral efficiency KPI can be calculated as the peak data rate divided by the maximum bandwidth of the system BW_{max} in Hz (including the frequency bands).

$$SE_p = \frac{Rate_p}{BW_{max}}$$

4.3.2.3 Peak BICM spectral efficiency

This KPI is calculated analytically using the following formula:

$$SE_{ps} = m_{max} \cdot CR_{max} \cdot N_{Tx/Rx}$$

where m_{max} and CR_{max} are the highest modulation and code-rate provided by a particular technology, respectively, and $N_{Tx/Rx}$ is the number of independent information spatial streams (i.e., with multiple transmit and receive antennas).

4.3.2.4 User plane latency

This KPI is calculated analytically as the time elapsed from when the source sends a packet to when the UE receives it. The terms in the calculations are for example: the UE processing delay, the frame alignment duration, the TTI for data packet retransmission, the HARQ retransmission duration and the BS (Base Station) processing delay [18].

4.3.2.5 Control plane latency

This KPI is calculated analytically as the time from a “battery efficient” state to an active state. The terms in the calculations are for example: the random access procedure duration, the UL (Uplink) synchronization duration, the connection establishment and HARQ retransmission duration and the data bearer establishment and HARQ retransmission duration.

4.3.3 Simulations

4.3.3.1 Link-Level Simulations

4.3.3.1.1 BICM spectral efficiency

This KPI is evaluated through link-level simulations. It is provided as BICM spectral efficiency (SE_{BICM}) vs CNR. The SE_{BICM} is calculated as:

$$SE_{BICM} = m \cdot CR_{eff}$$

where $m = \log_2 M$ with M being the cardinality of the used constellation per spatial stream (or antenna port in LTE systems) and CR_{eff} is the effective code-rate after the complete transmission chain. In LTE systems, the effective code-rate (after rate matching) is calculated as follows:

$$CR_{eff} = \frac{TBS}{N_b}$$

with TBS as the transport block size defined by 3GPP in [26], and N_b as the number of bits available for data transmission within a subframe (taking into account control symbols and reference signals).

4.3.3.1.2 Mobility

This KPI is a variant of the BICM spectral efficiency KPI, evaluated with link-level simulations by using a mobile channel model. In mobile environments, the channel realizations are a time variant function that depends on the relative speed of the transmit and receive pair. The time dependent variation of the channel realizations produces frequency shifts in the received signal known as the Doppler effect. The maximum frequency shift f_D in the received signal due to the Doppler effect is:

$$f_D = \frac{v\, f_c \cos\alpha}{c}$$

where v is the receiver velocity c is the speed of light, f_c is the carrier frequency of the signal, and α is the angle between directions of the receiver velocity and the arriving signal. The Doppler limit can be theoretically estimated as [28]:

$$f_{D_{limit}} = \frac{1}{2D_y(T_U + T_{CP})}\ Hz$$

where D_y is the length of the reference signal sequence in OFDM symbols, T_U is the useful symbol duration, and T_{CP} is the cyclic prefix length in time. Hence, the performance depends on the carrier spacing, system bandwidth, the operational frequency band and the accuracy of channel estimation.

4.3.3.2 Coverage Simulations

4.3.3.2.1 Coverage

Coverage can be calculated under different reception conditions such as fixed roof-top, portable (outdoor/indoor) and mobile. The differences between them are in terms of network topology or transmission density and link budget, as explained in Annex A. The coverage of a specific area needs to be determined by a combination of prediction methods together with system and network-specific parameters.

Reception of broadcast systems is defined on the basis of a “threshold”. The spectral efficiency of the system is fixed according to the modulation and codification parameters configured and the coverage depends on the access to the service, the time availability, and the location availability.

The performance of the system will depend on several additional factors such as the channel model adopted as reference (i.e. Rayleigh, Rice, TU6 (6-tap Typical Urban), etc.) and the error rate criteria (e.g. BER < 10^{-11}). These conditions can be evaluated by means of link-level simulations and result in a particular SNR threshold, SNR_{th}, that guarantees QEF (quasi error free) reception of the transmitted data. On the other hand, the kind of the network implemented (SFN or MFN (Multi-Frequency Network)), the reception type (e.g. fixed, portable, mobile, indoor), and other features related to the reception environment (e.g. presence of interferences, man-made noise, etc.) lead to an available SNR at the receiver input, SNR_{rx}. The available SNR_{rx} at the receiver can be calculated analytically by means of the link-budget characterization which accounts for the gain or loss factors of the elements in-between transmitter and receiver. Receiver locations with a larger or equal SNR_{rx} than the SNR_{th} are considered as covered.

The service "time availability" can be defined if the threshold is accomplished for any time interval. The assessment of the time availability considers time-variant factors at both transmitter and channel (e.g. propagation effect, interferences, etc.). Due to the random nature of these factors the available SNR may need to be assessed by means of simulation or with analytical approximations.

The service "spatial availability" is defined for small area coverage where, due to the variable nature of propagation in a given scenario (e.g. presence of shadow fading), SNR_{rx} varies from different receiving locations. The random nature of these processes requires the application of simulation methods or analytical approximations.

The complete description of the parameters considered for coverage evaluation is provided in Annex A.

4.3.3.3 System-level Simulations

4.3.3.3.1 User spectral efficiency

The user spectral efficiency is evaluated through system-level simulations for PTP. Let user i in drop j correctly decode $R_i^{(j)}(T)$ accumulated bits over a period T. For non-scheduled duration of user i zero bits are accumulated. During this total time user i receives accumulated service time of $T_i \leq T$, where the service time is the time duration between the first packet arrival and when the last packet of the burst is correctly decoded. In case of full buffer, $T_i = T$. Hence the rate normalised by service time T_i and carrier bandwidth W of user i in drop j, $r_i^{(j)}$, is:

$$r_i^{(j)} = \frac{R_i^{(j)}(T)}{T_i.\mathrm{W}}.$$

The 5th percentile user spectral efficiency shall be evaluated using identical simulation assumptions as the average spectral efficiency for that test environment [18].

4.3.3.3.2 Average cell spectral efficiency

The average SE (Spectral Efficiency) is calculated through system-level simulations for PTP. Let $R_i^{(j)}(T)$ denote the number of correctly received bits by user i $(i = 1, \ldots, N)$ (downlink) or from user i (uplink) over a time period T in a drop j. A system comprising a user population of N users and M TRxPs is considered. Further, let W denote the carrier bandwidth over which the data bits are received. The average spectral efficiency may be evaluated by running system-level simulations over a number of drops, N_{drops}. Each drop, j, gives a value of $\sum_{i=1}^{N} R_i^{(j)}(T)$ denoted as $R^{(1)}(T), \ldots, R^{(N_{drops})}(T)$ and the estimated average spectral efficiency resulting is given by:

$$\overline{SE} = \frac{\sum_{j=1}^{N_{drops}} \sum_{i=1}^{N} R_i^{(j)}(T)}{N_{drops}\, T.W.M},$$

where $\overline{SE}$ is the estimated average cell spectral efficiency that will approach the actual average with an increasing number of N_{drops}.

4.3.3.3.3 Reliability

The probability of a successful transmission within a predetermined time, assuming different application data types, is evaluated through system-level simulations.

4.4 KPI Evaluation

The results in this deliverable are structured around the different evaluation types considered, i.e. analytical, link-level simulations, coverage simulations and system-level simulations.

4.4.1 Inspection Evaluation

4.4.1.1 Bandwidth

ATSC 3.0 only allows a bandwidth allocation per RF carrier of 6 MHz and Channel Bonding (CB) of 2 RF carriers. Therefore, the maximum aggregated system bandwidth for ATSC 3.0 is 12 MHz.

LTE Rel'14 (SC-PTM and MBSFN) allows a maximum carrier bandwidth of 20 MHz and carrier aggregation of up to 5 RF carriers. Therefore, the maximum supported bandwidth is 100 MHz.

4.4.2 Analytical Evaluation

4.4.2.1 Peak BICM spectral efficiency

This section evaluates the peak BICM spectral efficiency provided by the digital terrestrial broadcasting standard ATSC 3.0 and the two PTM solutions of 4G LTE eMBMS, MBSFN and SC-PTM. The peak spectral efficiency depends on the maximum modulation order and (effective) code-rate.

ATSC 3.0 has in its specification a range of code-rates from 2/15 to 13/15 and a maximum constellation size of 4096 symbols. ATSC 3.0 uses as its outer code BCH codes which will be included in the calculation of the effective code-rate (although it is possible to configure the system without BCH coding). In this case, the maximum effective code-rate is 0.863.

LTE uses a maximum modulation order of 256QAM which was included from Rel'12. As presented in subsection 4.3.2 the effective code-rate is calculated as the TBS divided by the data bits dedicated to PTM within a subframe. Each MCS index provides a different effective code-rate, since they are directly related to a particular TBS. In LTE, the available bits for data are calculated as:

$$N_b = m \cdot N_{RB}(N_{symb} N_{sc}^{RB} - N_{ref})$$

Where m is the number of bits per subcarrier, N_{RB} is the number of RBs utilised, N_{symb} is the number of OFDM symbols per RB dedicated to the PTM service, N_{sc}^{RB} is the number of subcarriers per RB, and N_{ref} is the number of reference signals per RB. In SC-PTM, the number of OFDM symbols used for carrying control channel is 3 for 5 MHz and lower bandwidths, or 2 for 10 MHz and higher bandwidths. Therefore, the maximum number of bits with SC-PTM, when considering 100 RBs (BW 20 MHz), is:

$$N_{SCPTM}^{max} = 8 \cdot 100(12 \cdot 12 - 6) = 110400$$

In MBSFN, 3 different configurations are can be used depending on the carrier spacing selected. The maximum number of bits will change:

$$N_{MBSFN(15kHz)}^{max} = 8 \cdot 100(10 \cdot 12 - 18) = 81600$$

$$N_{MBSFN(7.5kHz)}^{max} = 8 \cdot 100(6 \cdot 24 - 18) = 100800$$

$$N_{MBSFN(1.25kHz)}^{max} = 8 \cdot 100(1 \cdot 144 - 24) = 96000$$

This can be observed in next figure, where framing configurations for a single RB and both SC-PTM and MBSFN with 15 kHz of carrier spacing are shown. The number of available data subcarriers per RB with MBSFN is 102, while SC-PTM uses up to 138. The number of bits can be calculated as the number of subcarriers multiplied by the modulation order m.

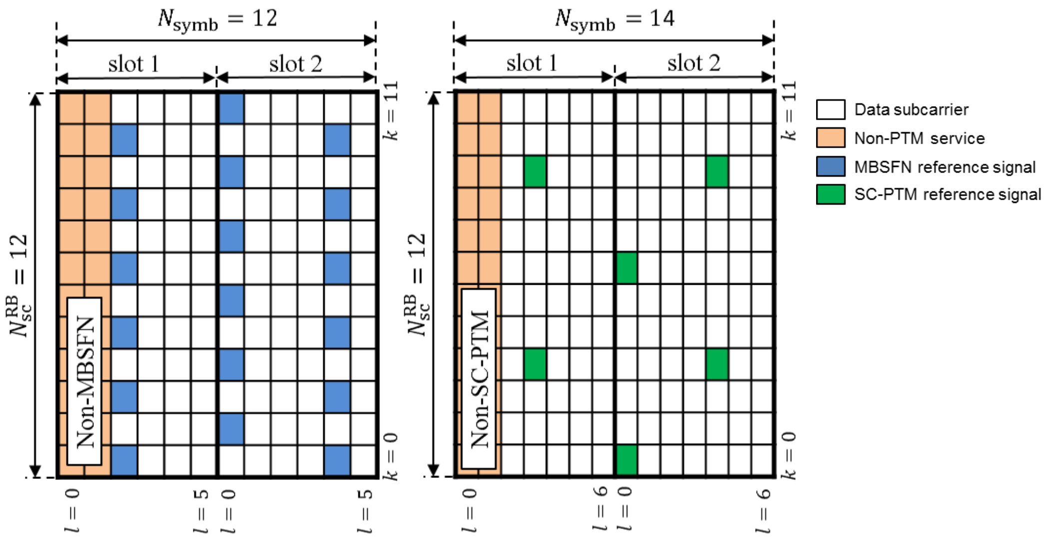

Figure 5: MBSFN (left) and SC-PTM (right) frame configurations for peak BICM spectral efficiency calculation. Both MBSFN and SC-PTM employ 15 kHz carrier spacing and BW 20 MHz.

In this deliverable, studies for MBSFN are focused on the standalone mode with 1.25 kHz of carrier spacing. This mode has been also considered in this analysis. The maximum TBS with SC-PTM and MBSFN is given for I_{TBS} = 33 and 32 respectively, and the associated code-rate is then calculated as follows:

$$CR_{SCPTM} = \frac{97896}{110400} = 0.887; \; CR_{MBSFN} = \frac{84760}{96000} = 0.882$$

The peak BICM spectral efficiency for each of the technologies considered is shown in Table 4. The SE calculated can be easily extended to MIMO by considering the number spatial streams (or antenna ports).

Table 4: Peak BICM spectral efficiency of ATSC 3.0, SC-PTM and MBSFN

	m_{max}	CR_{max}	SE_{ps}	SE_{ps} (MIMO 2x2)	SE_{ps} (MIMO 4x4)
ATSC 3.0	12	0.863	10.36	20.72	-
SC-PTM	8	0.887	7.09	14.18	28.36
MBSFN	8	0.882	7.06	-	-

4.4.2.2 Peak data rate

For ATSC 3.0, the peak data rate is obtained in two steps. The number of data cells on a frame is first calculated. Next, the number of net bits that can be assigned to the data cells previously estimated is obtained. The peak data rate is obtained for the configuration provided in Table 5.

Table 5: ATSC 3.0 parameters for the peak data rate

Parameter	Value	Parameter	Value
Frame duration	5 s	**Bandwidth**	6 MHz
FFT size	32k	**CP length**	192 samples
Bootstrap symbols	4	**Bootstrap symbol duration**	500 ms
L1-basic	163 cells	**L1-detail**	922 cells
C_{red_coeff} L1	4	**C_{red_coeff} Data**	0
Pilot Pattern	SP32_2	**Modulation order**	4096NUC
FEC block length	64800 bits	**LDPC code rate**	13/15
		BCH parity bits	192

Figure 6 illustrates the process carried out for obtaining the maximum number of data cells in a frame $DataCells_{frame}$ that an ATSC 3.0 system can transmit.

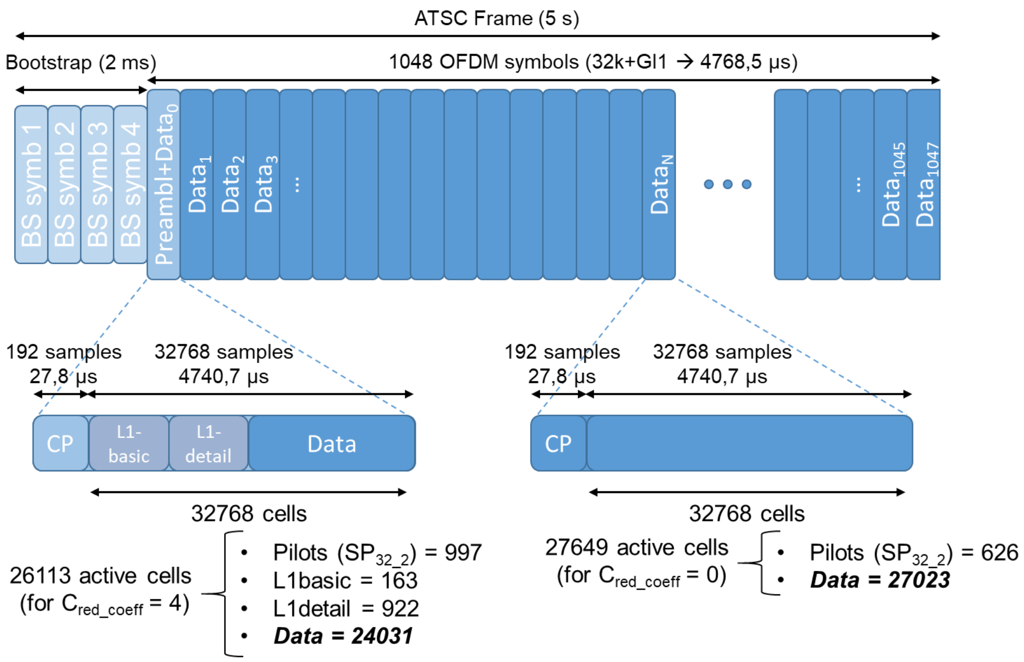

Figure 6: Maximum data cells that an ATSC 3.0 system can use.

From this configuration,

$$DataCells_{frame} = 24031 + 1047 \cdot 27023 = 28317112 \text{ cells}$$

where 24031 is the number of available data cells in the first preamble symbol, whereas the next 1047 OFDM symbols can use up to 27023 data cells each. Once the number of data cells has been derived, the peak data rate is obtained taking into account the constellation order, FEC block size, FEC coding rate, and frame duration as:

$$FEC_{Blocks} = \left\lfloor \frac{28317112 \cdot \log_2 4096}{64800} \right\rfloor = 5243$$

$$Rate_p = \frac{5243 \cdot (64800 \cdot \frac{13}{15} - 192)}{5} = \mathbf{58.70\ Mbps}$$

Therefore, the peak data rate is $Rate_p =$ **58.70 Mbps**.This second step is illustrated in Figure 7.

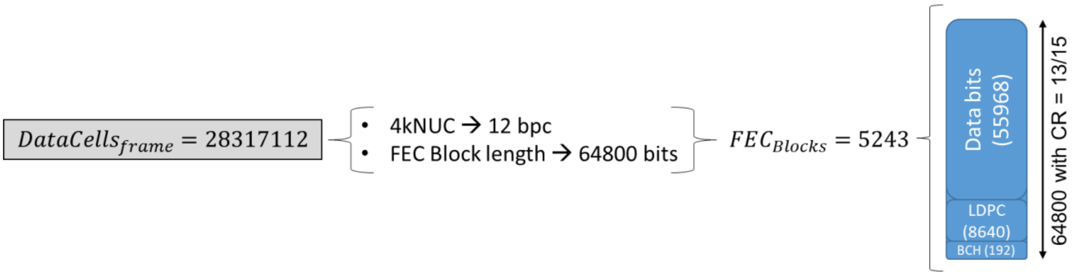

Figure 7: ATSC 3.0 peak data rate calculation (step 2).

This data rate can be doubled if MIMO 2x2 or channel bonding is used. ATSC 3.0 can provide in this case up to $Rate_p =$ **117.3 Mbps.**

Regarding LTE, SC-PTM and MBSFN allow to use different data rates once overheads have been taken into account, since the maximum TB size is limited for MBSFN and this technology also transmits for CAS one subframe every 40 ms. With SC-PTM, and taking the maximum bandwidth of 20 MHz, the peak data rate is $Rate_p =$ **97.9 Mbps**. Additionally, when considering MIMO for SC-PTM, the peak data rate is increased to $Rate_p =$ **195.8 Mbps** for 2x2 MIMO and $Rate_p =$ **391.6 Mbps** for 4x4 MIMO. On the other hand, the use of MBSFN limits the peak data rate to $Rate_p =$ **82.6 Mbps**.

Carrier aggregation can be also considered for this KPI calculation. The peak service data rate (without MIMO) in the case that carrier aggregation of 5 RF channels is $Rate_p =$ **489.5 Mbps** with SC-PTM and $Rate_p =$ **412.9 Mbps** with MBSFN

4.4.2.3 Peak spectral efficiency

The maximum TB size used in LTE when using a bandwidth of 20 MHz is 97896 for SC-PTM and 84760 for MBSFN, transmitted every TTI of 1 ms. The peak spectral efficiency for SC-PTM when using a SISO configuration can be calculated as:

$$SE_p = \frac{Rate_p}{BW_{max}} = \frac{97.9 \cdot 10^6}{20 \cdot 10^6} = 4.89\ \text{bits/s/Hz}$$

This calculation can be extrapolated to MIMO by modifying the maximum TBS as specified in [26]. The peak spectral efficiency for MBSFN is calculated as follows:

$$SE_p = \frac{Rate_p}{BW_{max}} = \frac{82.6 \cdot 10^6}{20 \cdot 10^6} = 4.13\ \text{bits/s/Hz}$$

The peak spectral efficiency for ATSC 3.0 is calculated taking into account the peak data rate obtained in the section below ($\text{Rate}_\text{p} = 58.70$ Mbps). This value is obtained for a SISO transmission in a 6 MHz channel bandwidth. Hence, ATSC 3.0 peak spectral efficiency is:

$$SE_p = \frac{58.70 \cdot 10^6}{6 \cdot 10^6} = 9.78\ \text{bits/s/Hz}$$

If MIMO 2x2 is taken into account, this value is doubled to $SE_p = 19.56\ \text{bits/s/Hz}$.

Table 6: Peak spectral efficiency of ATSC 3.0, SC-PTM and MBSFN

	SE_p	SE_p (MIMO 2x2)	SE_p (MIMO 4x4)
ATSC 3.0	9.78	19.56	-
SC-PTM	4.89	9.79	19.58
MBSFN	4.13	-	-

4.4.3 Link-Level Simulations

4.4.3.1 BICM spectral efficiency

The next subsections show the BICM spectral efficiency as a function of the CNR required to achieve a BLER 0.1% as described in Annex A. Different scenarios have been evaluated in order to assess the impact of the configurations adopted on each system:

- FEC codes and constellation shape robustness is evaluated in AWGN channel.
- Spatial Multiplexing capabilities of each technology are evaluated in a MIMO 2x2 i.i.d. Rayleigh channel.
- Additional time and frequency diversity provided by ATSC 3.0 time and frequency interleaving, respectively, is assessed for different reception scenarios:
    - Fixed-rooftop reception conditions, where the DVB-F1 channel is used.
    - DVB-NGH Portable Outdoor (NGH-PO) channel model, as specified in Annex A, is assumed in order to evaluate portable outdoor reception conditions.
    - DVB-NGH Portable Indoor (NGH-PI) channel model, as specified in Annex A, is assumed in order to evaluate portable indoor reception conditions.

4.4.3.1.1 SISO AWGN channel

Figure 8 (and Figure 9 in zoomed area) shows the BICM spectral efficiency in bits per channel use (bpc) as a function of the required CNR in an AWGN channel for SC-PTM, MBSFN, DVB-T2 and ATSC 3.0. In this study the goal is to compare the performance of the modulation and coding schemes of the different technologies. Hence, in the comparisons only Single Input Single Output (SISO) antenna configurations is considered. Note that LTE was designed to support multiple transmit and receive antennas from its very first release. With LTE, the use of at least two transmit and receive antennas has become the norm. However, in D3.1 only one receive antenna is considered to provide a fair performance comparison with ATSC 3.0 and DVB-T2. The channel capacity is also shown for comparison. The DVB-T2 performance results are obtained from Table 47 in [28] (note that these results do not include genie aided demapping). The results in this report for the LTE-Advanced Pro turbo-decoder uses a Max-Log-MAP decoding algorithm. As shown in annex E, this algorithm has a performance degradation (approximately 0.5 dB depending on the channel) compared to other decoding algorithms such as the true a-posteriori probability decoding but with the benefit of reduced computational complexity.

ATSC 3.0 provides important gains compared to LTE PTM, especially for high CNRs. DVB-T2 also outperforms LTE PTM but suffers a performance degradation compared to ATSC 3.0. Table 7 provides the CNR gains of ATSC 3.0 over DVB-T2 and LTE PTM technologies for different BICM spectral efficiency values:

Table 7: CNR thresholds in (dB) for ATSC 3.0 and the gains (in dB) of ATSC3.0 with respect to DVB-T2 and LTE PTM technologies in AWGN channel

BICM spectral efficiency	CNR for ATSC 3.0	NUC Gain	Gain of ATSC 3.0 over DVB-T2	Gain of ATSC 3.0 over MBSFN	Gain of ATSC 3.0 over SC-PTM
0.5 bpc	-2.9 dB	-	-	1.2 dB	1.2 dB
1 bpc	0.7 dB	-	0.3	0.8 dB	1 dB
2 bpc	5.8 dB	0.2 dB	0.5	1.1 dB	1.3 dB
3 bpc	9.8 dB	0.5 dB	0.3	1.6 dB	1.8 dB
5 bpc	16.2 dB	1 dB	0.6	1.5 dB	1.8 dB

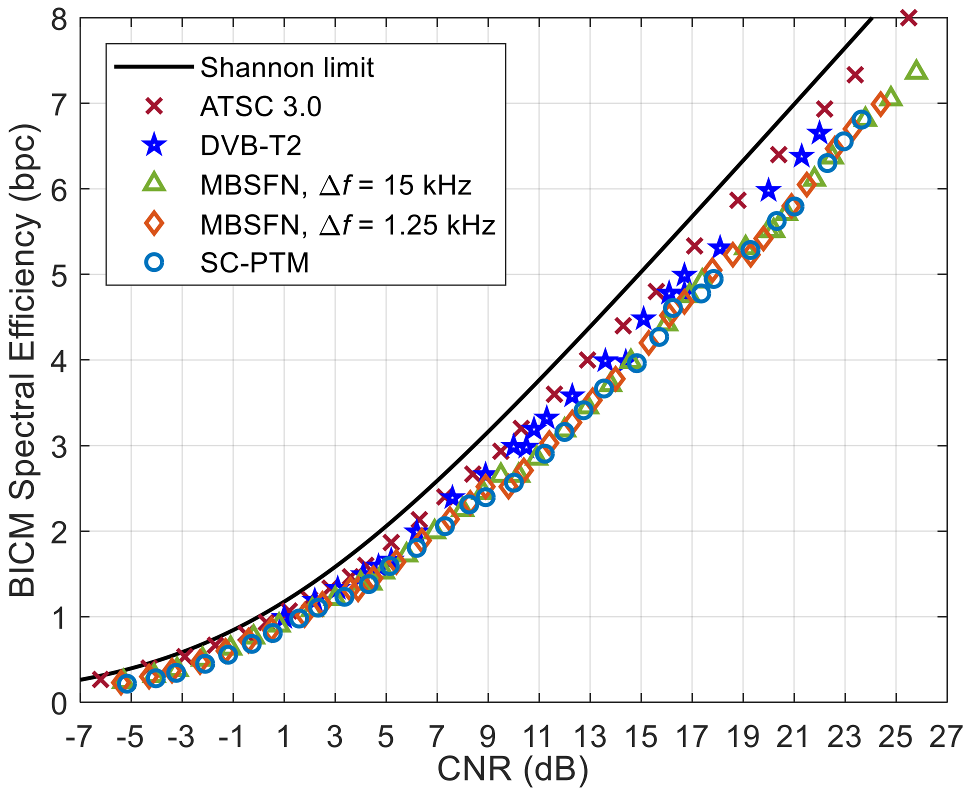

Figure 8: BICM spectral efficiency vs. CNR (dB) for SISO AWGN channel. LTE Rel’14 MBSFN, SC-PTM, DVB-T2 and ATSC 3.0.

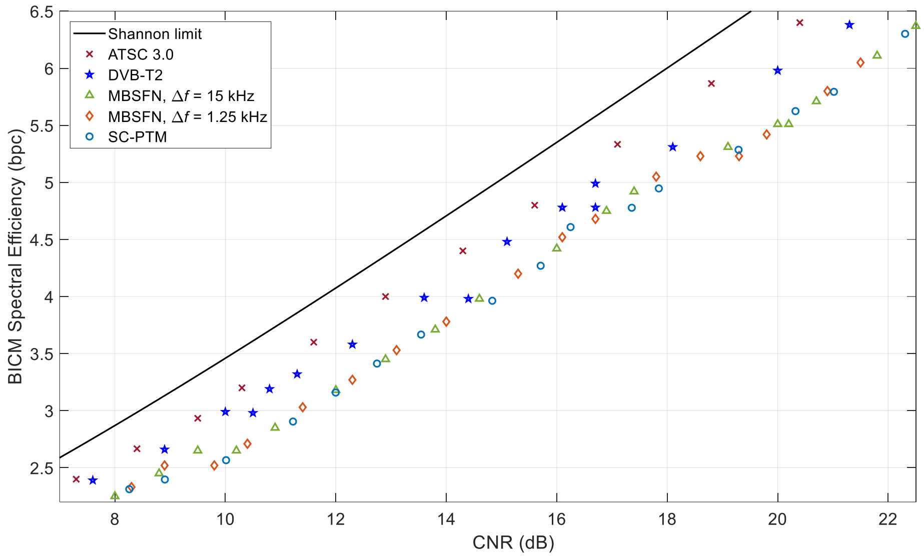

Figure 9: BICM spectral efficiency vs. CNR (dB) for SISO AWGN channel in zoomed area. LTE Rel'14 MBSFN, SC-PTM, DVB-T2 and ATSC 3.0.

The use of a more modern inner channel coding such as Long-Density Parity Check (LDPC) codes and Non-Uniform Constellations (NUC) for modulation provides significant performance gains for ATSC 3.0 compared to LTE PTM. NUCs introduced in ATSC 3.0 provide an important performance improvement due to the geometrical signal shaping, which increases with the constellation order. Table 7 also shows different NUC gains obtained for ATSC 3.0 and BICM spectral efficiencies of 2, 3 and 5 bpc as calculated in [27]. Note that no gains are obtained for 0.5 and 1 bpc, since the constellation used is QPSK and this constellation does not have room for possible optimization. Additional gains are obtained due to the use of longer codewords that in turn employ a long LDPC length of 64800 bits. The performance loss in ATSC 3.0 and DVB-T2 when using a shorter LDPC length of 16200 bits depends on the code-rate, introducing from 0.2 dB (high code-rates) to 0.7 dB (robust code-rates), regardless of the modulation order.

The overall performance of LTE follows the same trend regardless of the technology SC-PTM or MBSFN (and the different carrier spacing values). The use of a higher carrier spacing of 15 kHz instead of 1.25 kHz does modify the code-rate and therefore the required CNR to achieve 0.1% BLER, but on the other hand it also affects the BICM spectral efficiency.

The next subsections evaluate the performance on a MIMO i.i.d. Rayleigh, fixed-rooftop, portable outdoor and portable indoor channel models for the subcarrier spacing of Δf = 1.25 kHz for MBSFN. This assumption is based on the fact that the narrowest subcarrier spacing specified in Rel'14 will provide different performance compared to SC-PTM

4.4.3.1.2 MIMO i.i.d. Rayleigh channel

Figure 10 shows the BICM spectral efficiency versus required CNR for the independent and identically distributed (i.i.d.) Rayleigh MIMO channel with two transmit and receive antennas with a cross-polarization discrimination factor of $XPD = \infty$ (i.e. an ideal cross-polar channel where there is no depolarization of the transmitted signals). A Minimum Mean Square Error (MMSE) demapper has been used for this scenario with ATSC 3.0 and SC-PTM in order to cope with computation complexity limitations.

In this scenario, whereas ATSC 3.0 and SC-PTM utilise a MIMO scheme 2x2, instead MBSFN employs a 1x2 SIMO scheme (in this channel SISO and SIMO provide the same performance since there is no cross-polar component that can be exploited with two receive antennas). Hence, MBSFN cannot fully exploit spatial multiplexing gains compared with ATSC 3.0 and SC-PTM. It should be noted that SC-PTM uses open-loop MIMO without feedback from UEs. This is observed in the figure where MBSFN provides the lowest BICM spectral efficiency. Moreover, where MBSFN is limited to 7 bpc, SC-PTM and ATSC 3.0 can both increase their limits to 12 bpc.

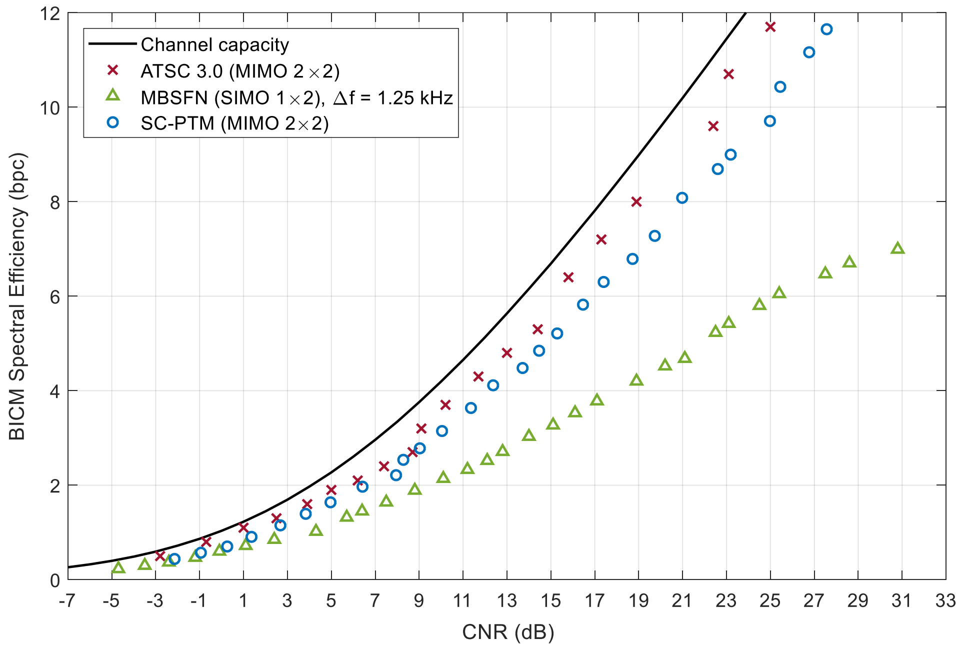

Figure 10: BICM spectral efficiency vs. CNR in dB of LTE Rel'14 MBSFN, SC-PTM and ATSC 3.0 for i.i.d. Rayleigh MIMO channel 2x2.

Table 8 provides ATSC 3.0 gains with respect to LTE PTM technologies for different BICM spectral efficiency values:

Table 8: ATSC 3.0 gains (dB) compared to LTE PTM, MIMO i.i.d. Rayleigh channel.

BICM spectral efficiency	Gain of ATSC 3.0 over MBSFN	Gain of ATSC 3.0 over SC-PTM
1 bpc	3.6 dB	1.4 dB
3.2 bpc	5.7 dB	1.1 dB
5.3 bpc	8.3 dB	1.1 dB
6.4 bpc	11.3 dB	1.9 dB
8.5 bpc	N/A	1.9 dB

Both ATSC 3.0 and SC-PTM with MIMO provide significant performance improvemebts over MBSFN without MIMO. The difference between ATSC 3.0 and SC-PTM ranges from 1 dB to 2 dB at low and high spectral efficiencies, respectively.

4.4.3.1.3 Fixed-rooftop environment

Figure 11 depicts the BICM spectral efficiency versus the required CNR for the DVB-F1 channel model, which is commonly used for modelling fixed-rooftop reception conditions [28].

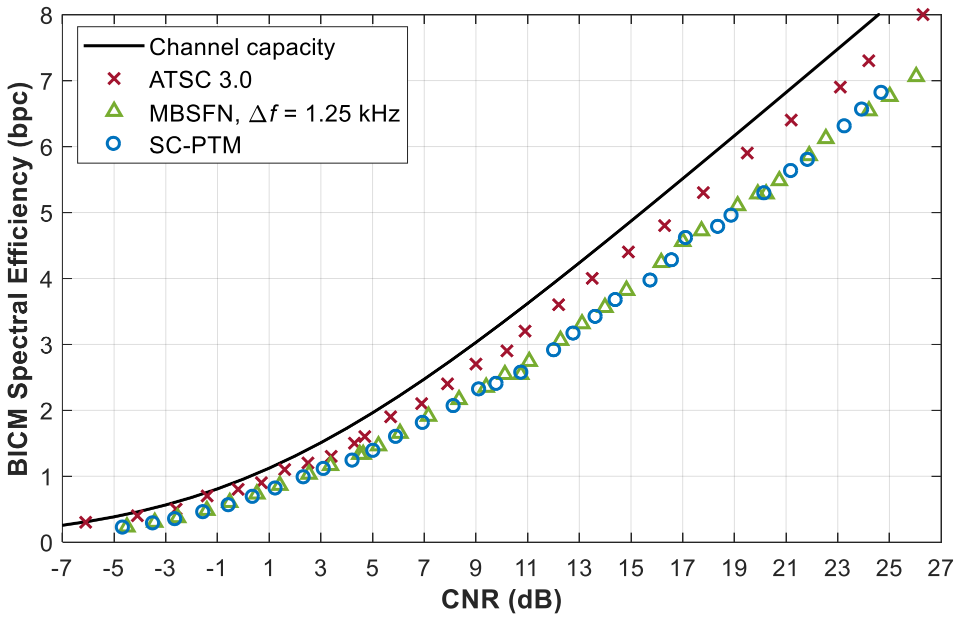

Figure 11: BICM spectral efficiency vs. CNR in dB of LTE Rel'14 MBSFN, SC-PTM and ATSC 3.0 for DVB- F1 Rice SISO channel.

Performance degradation for the three systems under evaluation can be observed compared to the performance obtained in an AWGN channel. The same trend as in previous channels is obtained namely that CNR thresholds are increased with respect to SISO AWGN channel around 0.1 to 0.3 dB for low spectral efficiencies and 0.4 to 0.7 dB for high spectral efficiencies.

A CNR value commonly used to model fixed rooftop reception in real scenarios is 20 dB. For the considered CNR, ATSC 3.0 provides a BICM spectral efficiency of 6.1 bpc. LTE, on the other hand, transmits 5.3 bpc (regardless of the PTM technology used) while requiring the same CNR. The ATSC 3.0 capacity gain for this scenario is therefore **0.8 bpc**. Table 9 also provides ATSC 3.0 gains in dB with respect to LTE PTM technologies for different BICM spectral efficiency values:

Table 9: ATSC 3.0 gains (in dB) with respect to LTE PTM technologies for fixed-rooftop reception conditions.

BICM spectral efficiency	Gain of ATSC 3.0 over MBSFN	Gain of ATSC 3.0 over SC-PTM
1 bpc	1.4 dB	1.3 dB
2 bpc	1.4 dB	1.6 dB
3 bpc	1.6 dB	1.8 dB
5 bpc	1.9 dB	2.4 dB

In comparison with Table 7, it can be observed that for 1 bpc BICM spectral efficiency, ATSC 3.0 is providing higher gains than the ones seen for the AWGN channel. This is due to the additional frequency diversity provided by the frequency interleaver and will be observed in more detail in the next scenarios.

4.4.3.1.4 Portable-outdoor reception

The NGH-PO models static reception at outdoor environments and due to the strong line of sight of the model it exhibits low frequency selectivity. Figure 12 shows the performance of the different PTM technologies evaluated. Due to the high computational burden that this channel model entails (i.e. a large number of channel snapshots need to be simulated to obtain statistically reliable results), only a representative set of LTE MCS indexes and ATSC 3.0 modulation and coding configurations are included.

A CNR value commonly used to model portable outdoor reception is 10 dB. In this particular case, ATSC 3.0 provides a BICM spectral efficiency of 1.9 bpc. A spectral efficiency of 1.4 bpc is obtained with SC-PTM, while MBSFN provides a slightly higher value of 1.6 bpc. The ATSC 3.0 capacity gain when using 100 ms time interleaving (TIL) for this scenario is therefore 0.5 and 0.3 bpc compared to SC-PTM and MBSFN respectively.

ATSC 3.0 provides higher gains than in previous cases for high BICM spectral efficiencies. This performance gain comes from the two additional interleavers of ATSC 3.0, i.e. time and frequency interleavers. When none of these interleavers are used, ATSC 3.0 performance depends on the LDPC code length. If LDPC code length 64800 bits is kept, the performance gets 1-2 dB worse than for cases with time and/or frequency interleaving. For 16200 bits LDPC code length, CNR degradation of 1-2 dB is obtained for robust ModCods and about 5-7 dB for high order ModCods. Overall, PTM technologies with short LDPC code lengths, like MBSFN or ATSC with 16200 bits, have significant degradation regarding CNR performance in comparison with long LDPC code length technologies.

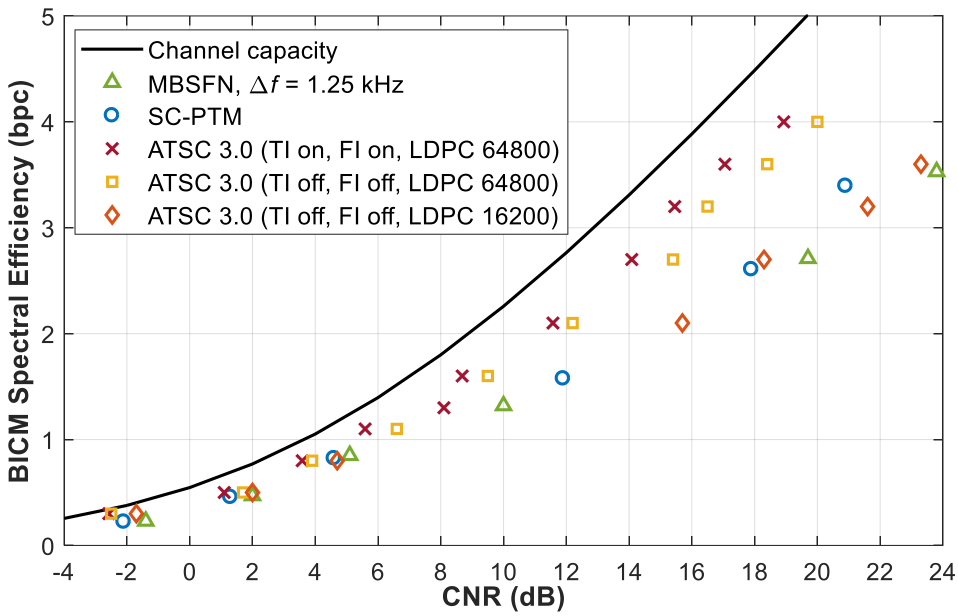

Figure 12: BICM spectral efficiency vs. CNR in dB of LTE Rel'14 MBSFN (Δ=1.25 kHz), SC-PTM and ATSC 3.0 for NGH PO.

4.4.3.1.5 Portable-indoor reception

NGH-PI models static reception at indoor environments and exhibits higher multipath with higher frequency selectivity than the NGH-PO channel. Figure 13 shows the performance of the different PTM technologies.

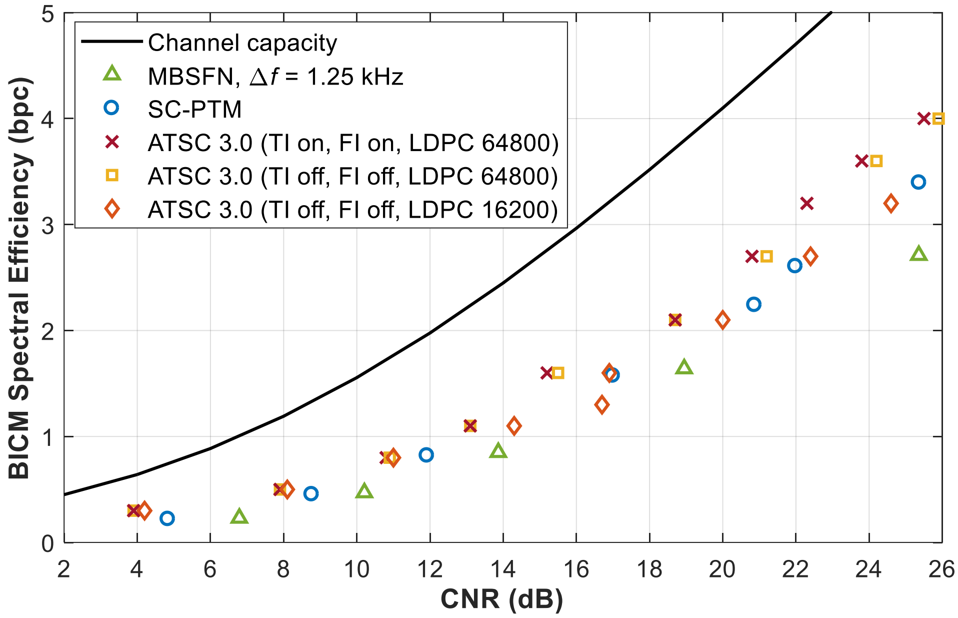

Figure 13: BICM spectral efficiency vs. CNR in dB of LTE Rel'14 MBSFN (Δ=1.25 kHz), SC-PTM and ATSC 3.0 for NGH Portable Indoor.

It can be observed that the channel capacity gap has been increased with respect to NGH-PO. This is because of a higher cross-polarization discrimination factor. Whereas NGH-PO is modelled with an $XPD = 4$, NGH-PI is defined with an $XPD = 1.78$. Hence, the direct channel component power is reduced.

The difference between both LTE technologies becomes larger with the CNR. The use of higher code-rates close to 1 degrades the performance significantly. The difference in CNR for the MCS 33 (256QAM, CR ~0.8/0.85) is higher than 5 dB.

For ATSC 3.0, when time and frequency interleavers are not used, CNR degradation depends again on the LDPC code length. For NGH-PI, this code length variation has a lower impact in CNR performance compared to NGH-PO channel, as a consequence of the power reduction of the direct channel component for this channel. An LDPC code length of 16200 bits can perform up to 3 dB worse in comparison with LDPC code length 64000, when neither time nor frequency interleaving is used.

4.4.3.2 Mobility

In order to evaluate the mobility performance of the three PTM technologies, the TU-6 channel model is used, see Annex A. Three different studies have been conducted for this KPI.

- For LTE MBSFN, forward error correction (FEC) at application layer (AL-FEC) is implemented in order to improve the robustness of the transmission.
- A first study with a fixed Doppler shift of 77.78 Hz and a wide range of LTE MCS indexes and ATSC 3.0 ModCods. For a carrier frequency of 700 MHz, this Doppler shift corresponds to 120 km/h receiver speeds.
- A second study for MBSFN where MCS indexes 3 and 15, which correspond to approximately 1 bpc and 2 bpc respectively, are evaluated for a wide range of Doppler shifts. The corresponding ATSC 3.0 ModCods QPSK 4/15 and 16NUC 9/15 are also considered for comparison.

In all studies, the following two time-diversity schemes have been considered:

- The selected subcarrier spacing for MBSFN is 1.25 kHz, having just one OFDM symbol that occupies the whole resource block. No TIL outside OFDM symbol (800µs) is possible. In this case, additional AL-FEC is evaluated.
- Subcarrier spacing of 15 kHz is used for SC-PTM. TIL can be performed by means of scrambling and scheduling at the physical layer. Intra-RB could be adopted as potential technology, where all OFDM symbols within a RB (which depend on the numerology employed) are interleaved.
- Different time interleaving depths are used for ATSC 3.0. Convolutional TIL is used, since Single Physical Layer Pipe (S-PLP) mode is assumed. The convolutional TIL depth depends on the number of convolutional rows. 0, 512, 724, and 1024 convolutional rows were considered, which represent TIL for no time interleaver (ΔT = 0) and approximate TIL depths ΔT = {50, 100, and 200} ms, respectively [29].

4.4.3.2.1 Use of AL-FEC correction codes in MBSFN signals

AL-FEC mechanisms are included in order to recover packet losses derived from underlying layers, allowing correction of end-to-end errors in scenarios with considerable time variability, caused mainly by fast fading and shadowing.

The AL-FEC coding process is defined by three parameters: the protection period (T_p) measured in ms, which is the time interleaving depth achieved at the application layer, the code-rate and the source symbol size (T) measured in bytes. eMBMS AL-FEC encoding is based on Raptor codes with a very good performance. For the simulations ideal AL-FEC coding has been considered fin order to simplify the obtained results.

With T having the same size than as a transport block, FEC blocks are created in order to constitute IP Packets, in this case with size 1024 bytes. The code-rate determines the number of erroneous packets that can be corrected. Lower code-rates increase AL-FEC protection against errors, but also increase the overhead to be transmitted. The protection period fixes the time length for source blocks transmission and is selected depending on the desired delay and memory available at the device. Longer protection periods take advantage of the temporal diversity but also increase the end-to-end delay and zapping time, which has an impact on the QoS.

In Figure 14, the AL-FEC performance is compared in two different scenarios, low temporal diversity and high temporal diversity, considering different code rates and protection period values. As can be observed, AL-FEC coding provides an important gain in mobile scenarios with time variability. However, AL-FEC is not efficient in scenarios with fixed channels due to the lack of time diversity.

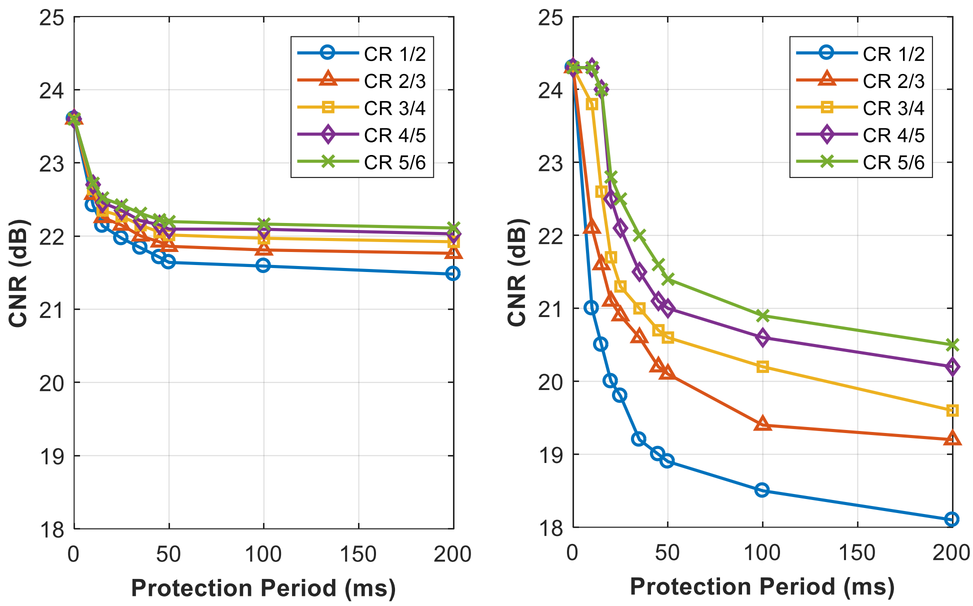

Figure 14: CNR vs. Protection Period in low diversity and in high diversity scenarios for several CR of AL-FEC MBSFN for MCS 21. Low diversity (left): NGH-PO channel with 3 km/h at 700 MHz carrier frequency. High diversity (right): TU-6 mobile channel with 120 km/h at 700 MHz carrier frequency.

4.4.3.2.2 Vehicular (120 km/h) reception

Figure 15 shows the BICM spectral efficiency versus CNR.

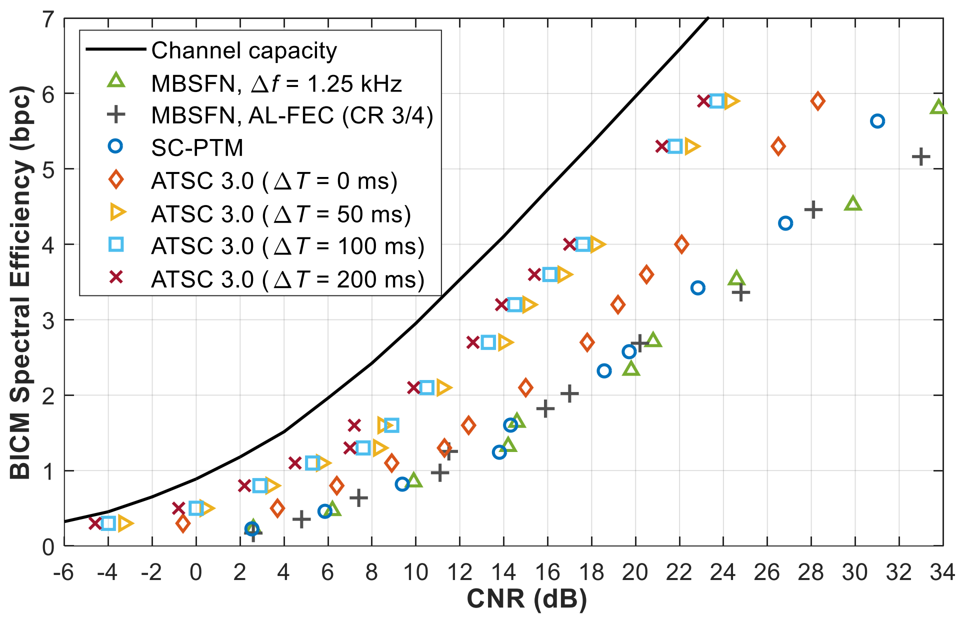

Figure 15: BICM spectral efficiency vs. CNR in dB of LTE Rel'14 MBSFN, SC-PTM and ATSC 3.0. TU-6 mobile channel with 120 km/h at 700 MHz carrier frequency.

ATSC 3.0 results show that the use of TIL provides large gains, regardless of the modulation order and code-rate used. Gains of 4-5 dB are obtained for ATSC 3.0 when using the maximum depth of $\Delta T = 200$ ms. If the shortest depth of $\Delta T = 50$ ms is used, gains range from 2.7 dB up to 4 dB. The performance of SC-PTM and MBSFN in mobile scenarios is worse than ATSC 3.0 even when considering no TIL. The use of time interleaving in SC-PTM can provide important performance gains by just using short TIL lengths, although this approach would require interleaving of more than one subframe. For MBSFN, no TIL at the physical layer is considered due to the subcarrier spacing of 1.25 kHz but AL-FEC is evaluated with configuration parameters: CR 3/4 and T_p = 100 ms.

For high MCS indexes, some MBSFN AL-FEC cases provide better performance than simple MBSFN cases while keeping the same BICM spectral efficiency. For low MCS indexes, AL-FEC gains become negligible. If longer protection period is used, CNR performance increase is obtained but also the latency becomes greater. Therefore, it can be considered that AL-FEC MBSFN can improve the reception for mobile channels with time diversity when no TIL is done at the physical layer.

Some alternatives like moving down AL-FEC to link layer or to physical layer can improve the performance in terms of latency and robustness, but at the expense of increased memory requirements at the receivers, e.g. BB-iFEC proposal for DVB-NGH [31].

4.4.3.2.3 Speed tolerance with practical receiving algorithms

For this study, a wide range of Doppler shifts is evaluated. A frequency band of 700 MHz has been used for MBSFN and ATSC 3.0 technologies. SC-PTM has not been considered in this study because of the use of a different frequency band and the higher carrier frequency spacing. The corner case in LTE PTM is MBSFN with a narrow carrier spacing of 1.25 kHz, which makes difficult the demodulation in mobile environments due to the Doppler shift introduced. The relationship between Doppler shift and speed for the two frequencies considered is shown in next table.

Table 10. Doppler shift (Hz) used in simulations for different technologies and related speed (km/h) for 700 MHz band.

Doppler shift (Hz)	User speed (km/h)
10	15.4
50	77.1
100	154.3
200	308.6
500	771.4

The theoretical Doppler limits of each PTM technology can be calculated as:

$$f_{D_{ATSC30}} = \frac{1}{2D_y(T_U + T_{CP})} = \frac{1}{2 \cdot 2 \cdot (1333.3\ \mu s)} = \mathbf{187.5\ Hz} \propto \mathbf{290\ km/h}$$

$$f_{D_{MBSFN}} = \frac{1}{2D_y(T_U + T_{CP})} = \frac{1}{2 \cdot 2 \cdot (1000\ \mu s)} = \mathbf{250\ Hz} \propto 385\ km/h$$

Figure 16 shows the CNR versus different Doppler shifts with real channel estimation. The estimation is constituted by a Least Square (LS) estimator on reference signals, followed by a 2-D linear interpolation in time and frequency domain.

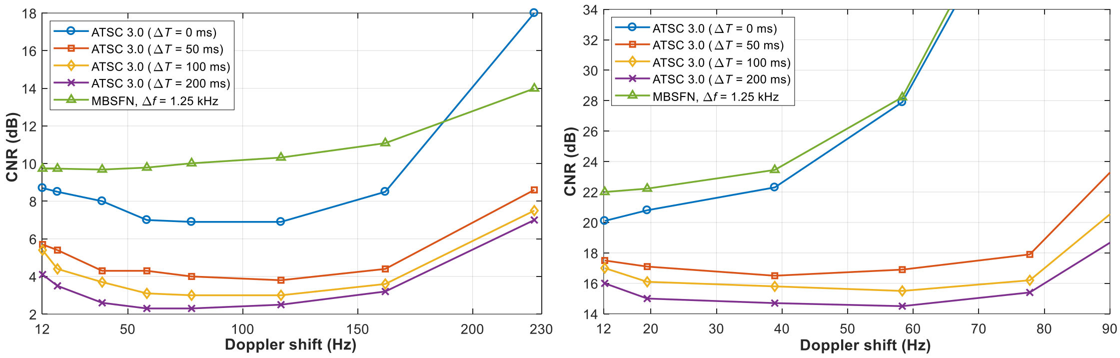

Figure 16: CNR to achieve a BLER 0.1% against user speed for LTE Rel'14 SC-PTM, MBSFN and ATSC 3.0 inTU-6 mobile channel. Left: MCS index 3 vs. QPSK 4/15. Right. MCS index 15 vs. 16NUC 9/15.

Results in Figure 16 (left) show that for Doppler shifts up to 150 Hz (user speeds of 225 km/h), the performance with ATSC 3.0 and real channel estimation is good enough to keep a good CNR. In this case, the higher the speed the lower the CNR required. This behaviour can be observed for both MBSFN and ATSC 3.0 when there is no time interleaving. However, for higher user speeds, the Doppler shift starts to cause significant Inter-Carrier Interference (ICI) and channel estimation errors. This leads to performance degradation. The only way to increase the Doppler shift limits is by using a time interleaver, as observed for ATSC 3.0. TIL also decreases the CNR regardless of the user speed under evaluation.

A similar behaviour can be observed in Figure 16 (right), for a higher MCS 15. ATSC 3.0 uses an equivalent ModCod of 16NUC 9/15. In this case, the Doppler shift permitted is drastically decreased due to the use of a less robust configuration. Moreover, the performance with MBSFN and ATSC 3.0 without TIL becomes really poor. Both technologies require very high CNRs to demodulate correctly the signal, and the CNR increases with the Doppler shift from the lower possible value. For example, a user speed of 90 km/h (around 60 Hz) is enough to increase the CNR in 6-8 dB compared to the static case.

From mobility link level simulations, it can be concluded that the proposed MBSFN 1.25 kHz carrier spacing, designed for large SFN coverage areas does not cope with 5G NR mobility requirements. Other alternatives should be studied, such as the use of TIL, denser pilot patterns or higher carrier spacing.

4.4.4 Coverage Evaluation

In this section the coverage performance of state-of-the-art terrestrial broadcasting technologies (LTE Release 14, SC-PTM and ATSC 3.0) is evaluated. Different aspects are analysed in connection to two network topology approaches: LPLT (Low-Power Low-Tower) and HPHT (High Power High Tower) [41]. Traditional broadcast networks are mainly based on elevated transmitting sites (in-between 150 to 300 m antenna height) transmitting dozens of kW ERP. LPLT topologies are the general topologies in cellular networks with denser deployments, antenna height of about 30 m and a few kW ERP.

Terrestrial broadcasting standards have been traditionally focused on service provision over HPHT topologies whereas LTE technologies have been deployed over LPLT topologies. LTE Release 14 has been improved with the implementation of a receive-only mode with 200 µs that could potentially enable operation in HPHT topologies. The impact on coverage that various factors, such as the OFDM parameters (cyclic prefix, symbol period, pilot pattern, etc), have been assessed in connection to SFN operation.

As well, the effects of various frequency reuse factors have been considered along with the impact of interference between different networks at regional or national borders.

Consideration has also been given to the performance of the system discovery and synchronization mechanisms. In particular, the system discovery mechanism in LTE Release 14 via the CAS inserted when using the so-called receive-only mode.

Finally, a general comparison of the coverage offered by the different broadcasting standards is provided under the different testing environments explained in Annex A.

4.4.4.1.1 Deployment strategies of terrestrial broadcast networks

PTM coverage over an arbitrarily large area would require transmission networks comprising multiple stations. Such networks are normally configured in the following two ways:

- **Multiple Frequency Networks (MFN)**, in which each station is assigned a different frequency to its neighbours in order to reduce interference between them. Each station transmits the same or different content compared with the others, and each station uses a different frequency to those nearby – see Figure 17 (left).
- **Single Frequency Networks (SFN)**, a group of transmitters, or cells, arranged in an SFN cluster in which the transmitters are time-synchronized in order to transmit the same content using the same frequency at the same time – see Figure 17 (right). The received signal in SFN is a series of echoes with different powers and delays according to the transmission channel and distance from the receiving point to each station. SFN supporting receivers are thus able to process the signal as artificial multipath. Thanks to the OFDM waveform and the insertion of a CP, signals that arrive within the CP contribute constructively whereas those with a larger delay introduce Inter-Symbol Interference (ISI).

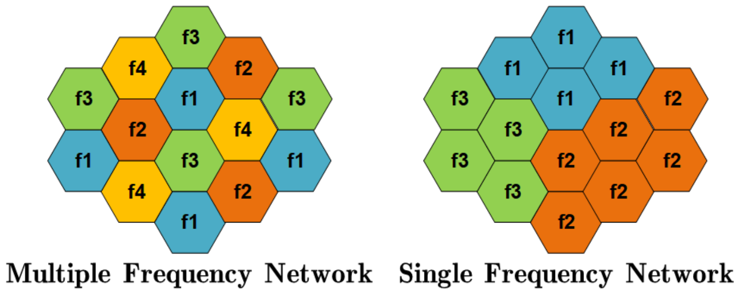

Figure 17: Hexagon-based topologies showing the Multiple Frequency Network (MFN) and Single Frequency Network (SFN) concepts

In order to provide contiguous coverage over the entire coverage area, both MFN and SFN normally use a different RF carrier in adjacent service areas when the content transmitted in one such area is different to the other (e.g. between different countries, regions or editorial areas). This mechanism is known as frequency reuse. Multiple frequencies can be used in order to increase the distance between co-channel stations (i.e., the reuse distance). This, in turn, reduces interference between co-channel stations and permits the capacity in each RF carrier to be increased. Increasing the number of frequencies in a network (i.e., increasing the reuse factor) reduces the number of available frequencies per transmitter. In an MFN, the frequency reuse is implemented at a cell level whereas for an SFN it involves a number of cells arranged in an SFN cluster, see Figure 17. Note that even for a large area SFN a certain frequency reuse is employed in order to avoid interferences between different regions or countries.

In some circumstances frequency reuse 1 – in which the same frequency is nominally used at all transmitters – is possible. For example, state-of-the-art cellular communications systems may operate in this way whereby interference mitigation techniques such as coordinated time-scheduling of radio resources may be used to mitigate or avoid interference.

It is important to include the frequency reuse factory when determining the spectral efficiency of a network. Although the available SINR per RF carrier may be higher in an MFN with a high re-use factor, thus increasing spectral efficiency per RF carrier, the number of active RF carriers per station decreases when increasing N. This effect can be measured in terms of the “Network Spectral Efficiency” as:

$$SpeEff_{Network} = \frac{SpeEff_{RF}(SINR_{dB})}{N}$$

Where $SpeEff_{RF}$ is the spectral efficiency per RF carrier and N is the frequency reuse factor. For the sake of comparison between different deployments, $SpeEff_{RF}(SNR_{dB})$ will be approximated by Shannon´s formula $SpeEff_{RF} = \log_2(1 + SINR)$.

4.4.4.1.1.1 Cyclic Prefix Insertion in SFN

The CP (referred to as GI – Guard Interval - in terrestrial broadcasting standards) is a cyclic extension of the useful time-domain symbol duration which consists of a fraction of the last part of the OFDM symbol that is appended to the beginning. The length of the CP needs to be longer than the channel impulse response, or in an SFN, longer than the maximum delay expected in the network. In general, the length of the CP should at least, accommodate the maximum separation between transmitters or inter-site distance (ISD). For demodulation, the receiver positions the FFT window according to a synchronization strategy as described in [43].

Figure 18 shows an example of the reception of three signals. Each signal is represented as an OFDM symbol with a useful part and a cyclic prefix. The receiver is synchronized to signal 2, such that signals 2 and 3 contribute constructively whereas signal 1 introduces ISI. The FFT window positioning is synchronized to the strongest signal (signal 2). It can be seen that synchronization approach corresponds to “strongest signal”. Signal 2 and Signal 3 contribute constructively whereas Signal 1 creates ISI.

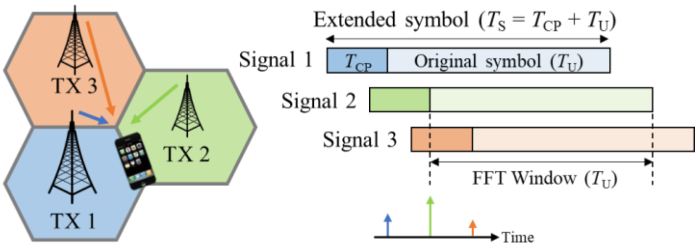

Figure 18: Signal received from 3 different transmitters in an SFN.

The implementation of SFN networks may improve coverage compared with an equivalent MFN thanks to signal diversity. The presence of several signals from different directions decreases the variability of the total signal field strength. Compared with an MFN, this effect reduces the overall location variation, resulting in lower field strength being required to meet a particular coverage requirement. On the other hand, the artificial multipath channel generated by the SFN implies larger frequency selectivity which may degrade the received signal.

The insertion of a CP represents an overhead that leads to a capacity reduction. Thus, the CP represents a trade-off between capacity overhead and robustness against multipath and maximum ISD in an SFN. To maximise the net bitrate, the CP is often chosen to be as small as in practical, reducing accordingly the maximum delay from natural multipath echoes and “artificial” echoes from distant SFN transmitters. The overhead introduced by the CP can be expressed as:

$$OH_{CP} = \frac{T_{CP}}{T_S}$$

Where T_{CP} is the CP duration and T_S is the OFDM symbol duration.

4.4.4.1.1.2 Pilot Pattern or Reference Signals

In SFN it is necessary that all stations transmit the same content. This requirement not only implies the structures carrying data but also the pilot sub-carriers for channel estimation, also referred to as reference signals. These must be co-located in the time and frequency domains at different transmitters. In general, pilot patterns in SFN should have a close spacing in the frequency domain due to the frequency-selective nature of the channel frequency response of these channels characterized by deep notches caused by lengthy signal echoes.

All pilot patterns are characterized by two parameters:

- D_X: the frequency domain spacing between pilot-carrying subcarriers, measured in the number of carriers,
- D_Y: the time-domain difference between successive pilot subcarriers measured in units of OFDM symbols.

Note that two consecutive pilot subcarriers are not necessary located in the same OFDM symbol [44].

The selection of the pilot pattern presents implications in the coverage performance of an SFN. The channel is properly estimated as soon as the maximum delay between the first and last paths of the channel impulse response are less than or equal to the Nyquist channel extent. C). In this sense, the Equalization Interval needs to be larger than the CP duration.

The pilot pattern introduces a compromise between capacity and the ability to correctly estimate the channel. The overhead introduced can be expressed as:

$$OH_{PP} = \frac{1}{D_X D_Y}$$

In order to study the cost of a larger CP overhead and perform a fair comparison of numerologies with different CP overhead, the SINR needs to be mapped in the spectral efficiency domain. One such mapping is shown below:

$$SpeEff = SpeEff_{RF}(SNR_{dB}) * (1 - OH_{CP}) * (1 - OH_{PP})$$

where OH_{CP} is the overhead due to the CP over the OFDM symbol length and OH_{PP} is the overhead due to the pilot pattern. $SpeEff_{RF}$ is the spectral efficiency per RF carrier.

4.4.4.1.2 Numerology and OFDM Parameters for SFN Operation in State-of-the-Art Technologies

4.4.4.1.2.1 eMBMS Release 14

LTE Rel’14 defines a number of different numerologies. These are summarised in Table 11 where it can be seen that three sub-carrier spacings (Δ_f), combine with four different CP durations (T_{CP}), creating four different numerologies with the useful OFDM symbol durations (T_U) as shown. The normal CP (4.7 µs) and 15 kHz sub-carrier spacing is not defined for MBSFN subframes. Note that, in order to completely fill the slot, the first OFDM symbol of the normal CP has a longer 5.2 µs duration (cf. 4.7 µs otherwise). MBSFN operation enables three extended CP options. A CP of 16.67 µs duration with 15 kHz Δ_f is available, as is a longer 33.3 µs CP with Δ_f of 7.5 kHz. By decreasing Δ_f to 1.25 kHz, Release 14 has introduced a new extended 200 µs CP. In all cases the overhead due to the CP is 20%. As shown in Table 11, the maximum ISDs for the two short CPs are 5 km and 10 km, which are only practical in LPLT networks. The new CP extends the ISD up to 60 km which may also be used in HPHT deployments.

Table 11: Numerology options in Release 14 for SFN operation.

	Δ_f (kHz)	# subcarriers / RB	# OFDM symbols per subframe	T_{CP} (µs)	T_U (µs)	Overhead	ISD (km)
Normal Unicast	15	12	7	4.7 5.2 (1st)	66.7	6.5%	1.4
Extended	15		6	16.7	66.7	20%	5
	7.5	24	3	33.3	133.3	20%	10
	1.25	144	1	200	800	20%	60

The selection of particular OFDM parameters has an impact on the structure of the frames. Each frame (10 ms) is composed of 10 subframes (1 ms) comprising 2 slots (0.5 ms). In the 200 µs CP variant the OFDM symbol occupies the entire duration of a sub-frame. In this case, the unicast control region in MBSFN subframes has been eliminated. The eMBMS modes have an associated set of reference signal patterns that are denser in the frequency direction compared with the standard unicast patterns. These help the receiver correctly equalise the channel in the presence of 'artificial' echoes with long delays generated by distant transmitters in the SFN. Each cell belonging to an MBSFN area transmits the same MBSFN reference signal pattern at precisely the same time-frequency position.

As shown in Figure 19, for the 15 kHz sub-carrier spacing variants, known reference symbols are inserted in every other sub-carrier in the 3rd, 7th and 11th OFDM symbol of each sub-frame, with a single sub-carrier offset in the 7th OFDM symbol. In the 7.5 kHz sub-carrier spacing variant, one reference signal is inserted in every four sub-carriers in the 2nd, 4th and 6th symbols of each sub-frame, as shown. In the 1.25 kHz variant, one in six sub-carriers is occupied by reference symbols, also with an offset on odd vs even sub-frames, as shown.

With respect to multipath, or echoes – either artificial or natural – the frequency spacing between pilots determines the length of delay up to which the channel may be correctly equalised when using time-frequency interpolation. Delays up to the duration of the equalization interval (EI) may be tolerated.

The EI is calculated assuming that the receiver is able to perform time and frequency interpolation. A factor of 57/64 is considered to account for realistic receiver implementation. According to the frequency separation between reference signals D_x, the EI for MBSFN subframes is 59.3 µs for Δ_f 15 kHz and 7.5 kHz and 237.5 µs for Δ_f 1.25 kHz.

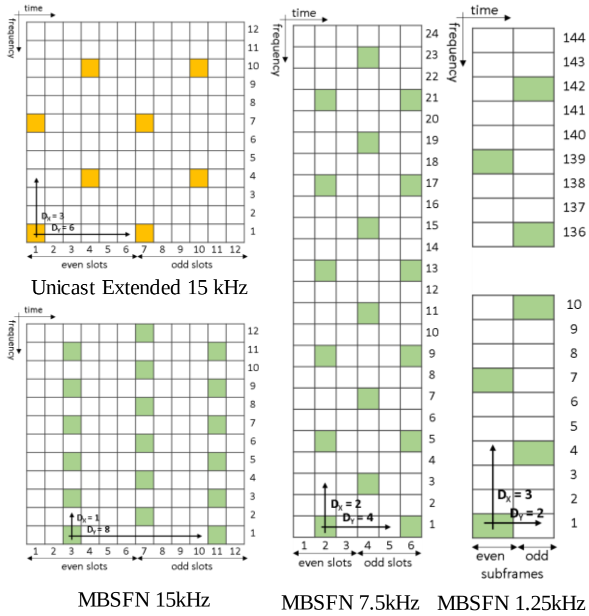

Figure 19: Mapping of MBSFN reference signals for $\Delta_f = 15\ kHz$, $7.5\ kHz$ and $1.25\ kHz$.

The capacity overhead introduced by the MBSFN reference signals is 12.5%, which is constant for the 3 sub-carrier spacings.

4.4.4.1.2.2 SC-PTM

SC-PTM does not support SFN operation. The only option is MFN with each eNB employing a different frequency or with frequency reuse 1, in which case the network would suffer from severe interference. In this case, the normal CP (unicast) is used, as shown in the first row in Table 11.

4.4.4.1.2.3 ATSC 3.0

ATSC 3.0 offers a much wider range of configuration options compared with Release 14. It is therefore much more flexible and it is possible to adjust the overhead/gain trade-off with larger granularity. For example, the longest CP in ATSC 3.0 is 3.5 times greater than Release 14, supporting ISDs up to around 211 km compared with around 60 km in Release 14.

Conversely ATSC 3.0 system bandwidth is fixed so that increasing the FFT size decreases sub-carrier spacing while increasing the symbol period. Thus the overhead decreases for large FTT size. The FFT sizes available are 8k, 16k and 32k FFT with corresponding OFDM symbol durations of about 1185 µs, 2370 µs and 4740 µs in a 6 MHz RF carrier. As an example, the following figure states the overhead difference for 300 µs CP for 8k and 32k FFT sizes.

Figure 20: Relation between OFDM symbol length and CP overhead.

ATSC 3.0 offers 12 different CP durations as set out in Table 12 along with indicative ISDs and overheads that the numerologies support.

Table 12: Cyclic Prefix options in ATSC 3.0.

CP (# Samples)	Δ (µs)	Overhead (%)			ISD (km)
		8k	16k	32k	
GI1 (192)	27.87	2.3	1.2	0.6	8
GI2 (384)	55.56	4.7	2.3	1.2	16
GI3 (512)	74.07	6.3	3.1	1.6	22
GI4 (768)	111.11	9.4	4.7	2.3	33
GI5 (1024)	148.15	12.5	6.3	3.1	44
GI6 (1536)	222.22	18.7	9.4	4.7	66
GI7 (2048)	296.30	25.0	12.5	6.3	88
GI8 (2432)	351.85	29.7	14.8	7.4	105
GI9 (3072)	444.4	N/A	18.8	9.4	133
GI10 (3648)	527.78	N/A	22.3	11.1	158
GI11 (4096)	592.59	N/A	25	12.5	178
GI12 (4864)	703.70	N/A	N/A	14.8	211

Figure 21 (left) shows a comparison in terms of the additional overhead in eMBMS R14 with respect to ATSC 3.0 for the available CP values (translated into maximum inter-site distances) between 10 km and 60 km. It can be seen that the lack of a finer CP granularity in LTE Release 14 may suppose an important capacity reduction. As an example, for a maximum ISD of 40 km, the ATSC 3.0 148.15 µs CP supposes an overhead between 3% (32k FFT) and 12% (8k FFT) while the overhead in Rel'14 is 20%.

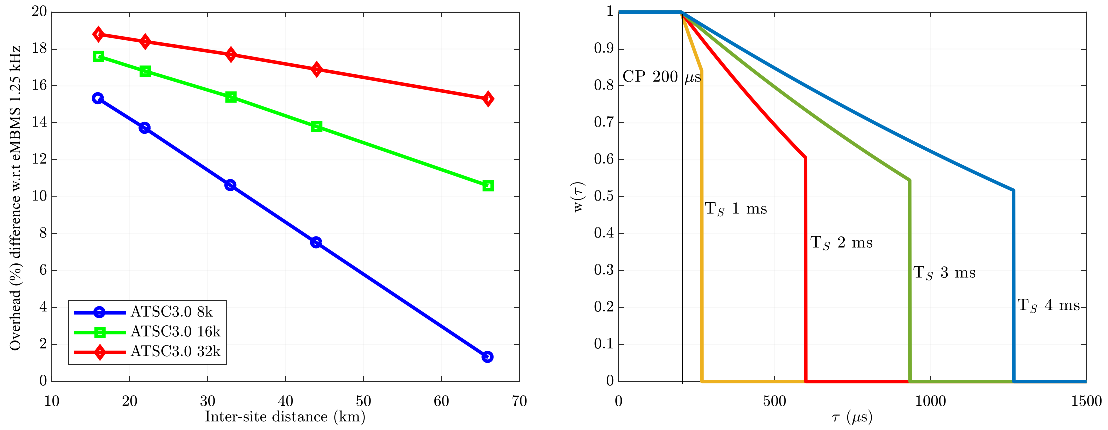

Figure 21: CP overhead comparison between ATSC 3.0 and LTE 1.25 kHz (left). Impact of the OFDM symbol duration in the weighting function of constructive and destructive signals in an SFN (right).

Furthermore, the use of a longer OFDM symbol not only reduces capacity overhead but increases system performance against echoes. In this sense, increasing T_U leads to a proportional increase of the equalization interval so that part of the power of the signals outside the CP contribute constructively, see Figure 21 (right).

ATSC 3.0 defines 16 scattered pilot (SP) schemes, see Table 13 [45]. The terminology employed is SPD_X_D_Y. As can be seen from the table, the overhead ranges from 0.78% up to 16.6%.

Table 13: Pilot Pattern options in ATSC 3.0.

Pilot Scheme	Dx	Dy	Overhead (%)	Pilot Scheme	Dx	Dy	Overhead (%)
SP3_2	3	2	16.6	**SP12_2**	12	2	4.16
SP3_4	3	4	8.33	**SP12_4**	12	4	2.08
SP4_2	4	2	12.5	**SP16_2**	16	2	3.12

SP4_4	4	4	6.25	**SP16_4**	16	4	1.56
SP6_2	6	2	8.33	**SP24_2**	24	2	2.08
SP6_4	6	4	4.16	**SP24_4**	24	4	1.04
SP8_2	8	2	6.25	**SP32_2**	32	2	1.56
SP8_4	8	4	3.12	**SP32_4**	32	4	0.78

Note that ATSC 3.0 SP4_2 is equivalent to the MBSFN reference signals with overhead 12.5%. In this case the DTT standard provides two additional SP options with D_X = 3, which may improve channel estimation in the frequency domain.

4.4.4.1.3 MFN and SFN performance in HPHT and LPLT Topologies

A generic analysis of the coverage capabilities of broadcast systems has been conducted by means of hexagon-based network topologies and a set of parameters with a direct impact on the coverage such as the CP duration or the OFDM symbol duration. The evaluation is performed with the test environments for fixed roof-top reception (Annex A) with different parameters such as the ISD.

For the sake of comparison, the results are presented for two different types of network deployments consisting of MFN and an arbitrarily large SFN area. For the MFN, four different frequency reuse patterns are considered (*N* = 1, 3, 4, 7) in order to evaluate the effect of external interferences. For the SFN, self-interference has been evaluated as a function of ISD and CP length (for 33, 100, 200, 300 and 400 µs). The effects of interference at SFN area borders have also been evaluated as well as potential strategies to mitigate them. Layouts of the network used in the studies are shown in Annex A.

Figure 22 presents the available SINR, in dB, at the worst pixel of the central hexagon of the MFN. The values are computed for different location probability percentages from 50% to 99.9% and for test environment HPHT rooftop reception (see Annex A.4.1). The results show the degradation of the SINR when reducing the frequency reuse factor from 7 to 1. The SINR gap between reuse 1 and 3 is particularly noticeable while reuse 3 and 4 show a similar performance. For reuse 1, the SINR extends to negative values for high location probability percentiles. The plots on the right-hand side of the figure show the SINR distribution within the worst hexagon, where it can be seen that the most affected pixels are at the cell edge.

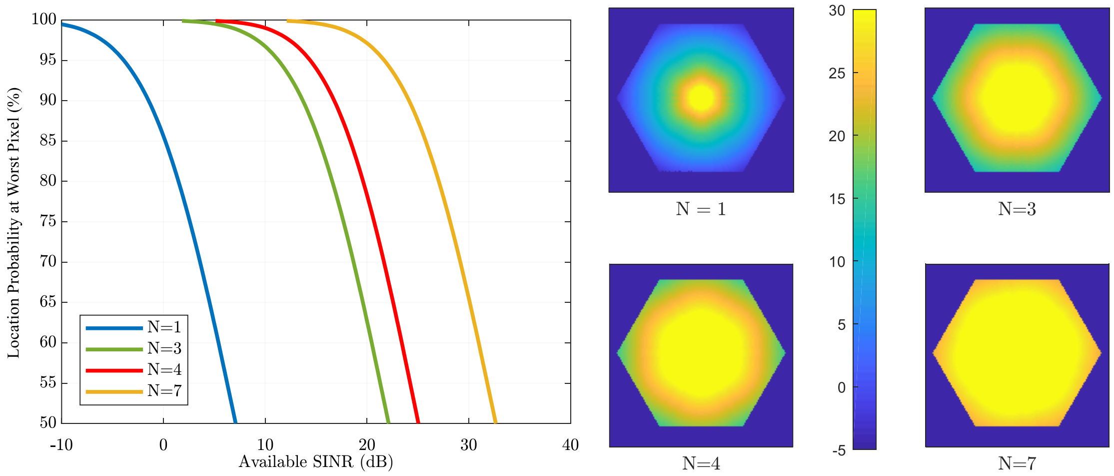

Figure 22: Available SINR as a function of location probability in HPHT MFN test environment with 60 km ISD (left). SINR values for different frequency reuse and location probability 95% (right).

A similar analysis was performed for the same receiving conditions but with an SFN as opposed to an SFN, as shown in Figure 23. In this case, the effect of selecting a different CP duration from 33 µs to 400 µs is observed. Note that in this case, the CP to OFDM symbol duration ratio is constant, meaning that the symbol duration increases according to the CP, the latter being set to 1/4th of T_U.

In this case the network is considered to be large enough so that only SFN self-interference is present. Thus, the result would apply, for instance, to an arbitrarily large SFN which does not receive interference from other networks, at least in its central part. Such an outcome could be achieved by means of frequency reuse at an SFN level. The results show that the worst pixel of the network is located at the centre of the lattice.

It can be seen that the 33 µs CP is clearly too short to provide a practical, high SINR in a network with an ISD of this magnitude. For the same reasons the 100 µs CP produces similar results. The 200 µs duration CP provides much better performance – the achievable SINR increases by around 10 dB. Although the 200 µs covers the maximum ISD of the SFN, increasing the CP up to 300 or 400 µs provides a further SINR improvement.

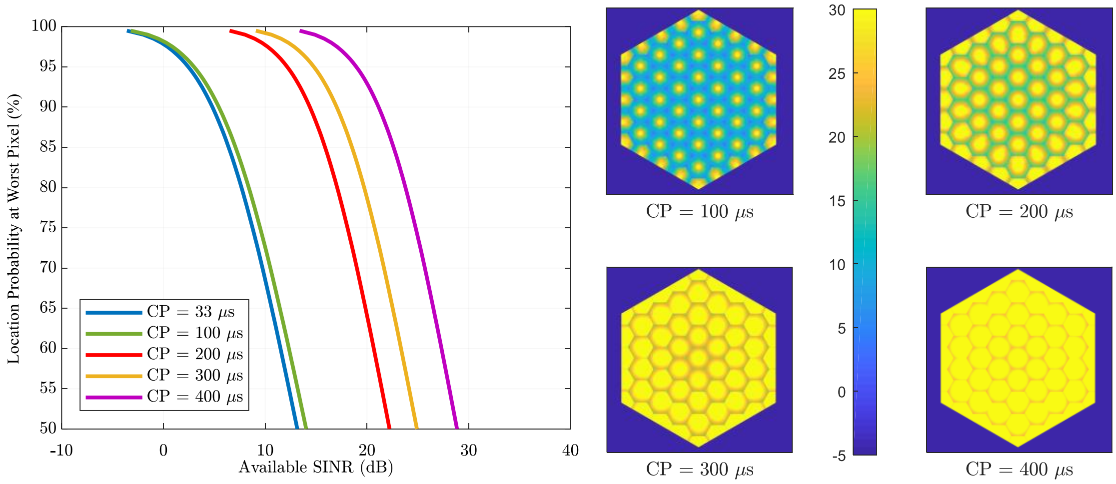

Figure 23: Available SINR as a function of location probability for different CP duration in HPHT SFN test environment with 60 km ISD (left). SINR values for different CP duration and location probability 95% (right).

In order to understand the effect of the ISD in both MFN and SFN deployments, the available SINR at the worst pixel in the network is computed as a function of the ISD for 70% and 95% coverage probability. Due to the fact that the path lengths from different transmitters are increased proportionally, the impact on the achievable SINR of different ISDs in MFN is minimal, as is shown in Figure 24 (left).

On the other hand, the ISD has a pronounced impact on the SFN. In these networks – for a given CP – the number of transmitters contributing constructively to the wanted signal increases for shorter ISD, while the interfering signals decrease at the same time. Figure 24 (right) shows the available SINR as a function of the ISD and the CP duration. CPs 33 µs and 100 µs yield the same performance since the range of ISDs considered exceeds the maximum ISD distance encompassed by the CP durations – neither CP is long enough to encompass the 40 km, the smallest ISD considered. The benefit of longer CPs becomes apparent from 200 µs onwards. The 40 km ISD provides the highest SINR values whereas 50, 60 and 70 km show a similar performance. 80 km however, causes a reduction of the available SINR due to increased SFN self-interference levels.

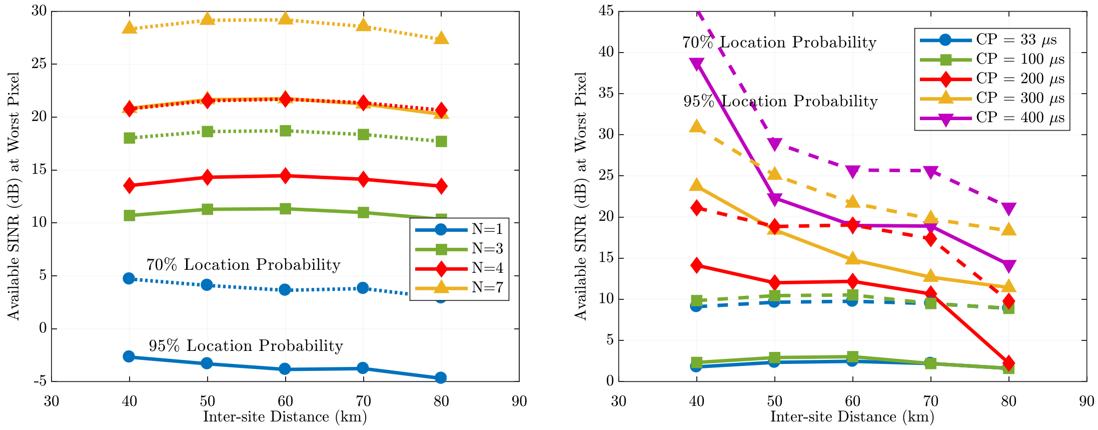

Figure 24: Available SINR at the worst pixel of the HPHT network as a function of the ISD for different frequency reuse factors (MFN) and different CP duration (SFN) (right).

The following table provides a summary of the minimum SINR for 95% locations in the example scenario with 60 km ISD. The table provides the available SINR at the worst pixel for 95% location probability as well as the spectral efficiency provided by the Shannon formula. A third column provides the network spectral efficiency taking into account the frequency reuse factor. In this case the network spectral efficiency serves as a fair comparison between different network deployments as the total amount of spectrum used (i.e. frequency reuse factor) to achieve a given capacity is taken into account. A similar table is shown for the SFN deployment with different CP duration. In this case, the third column provides two examples of the network spectral efficiency when considering that a frequency reuse of 3 or 4 (N3 and N4, in the table) is implemented in the network at SFN level. This is done to reflect the necessary frequency reuse between different networks that may be applied so that the SFN can be regarded as self-interference limited. Note that the effect of the interferences between different SFNs is treated in the following section.

Table 14: Spectral Efficiency in MFNs and SFNs for HPHT 60 km ISD

Multiple Frequency Network				*Single Frequency Network (Large Area)*			
N	**SINR (95%)**	**Spectral Efficiency (bps/Hz)**		**CP**	**SINR (95%)**	**Spectral Efficiency (bps/Hz)**	
		Shannon	**Network**			**Shannon**	**Network (N3/N4)**
1	-3.8 dB	0.50	0.50	100	3.0 dB	1.58	0.53/0.40
3	11.3 dB	3.86	1.29	200	12.2 dB	4.14	1.38/1.03
4	14.5 dB	4.87	1.22	300	14.8 dB	4.96	1.65/1.24
7	21.7 dB	7.22	1.03	400	19.0 dB	6.33	2.11/1.58

The results reveal that the most efficient deployment for the MFN would come from a frequency reuse 3 network since it provides the largest network spectral efficiency. Comparing this with the SFN, it can be seen that the 100 us CP results are clearly poor while the 200 µs and 300 µs CPs provide similar results to the reuse 3 and 4 MFN. A larger improvement from the 400 µs CP is noticeable. From the point of view of the network spectral efficiency, frequency reuse 3 applied to the SFN would result in an increased performance with respect to the same reuses in the MFN. However, for 200 us and 300 µs, if a reuse 4 is applied to the SFN the network spectral efficiency is found to be similar or even worse than in the MFN deployment.

A similar analysis has been conducted for LPLT networks. Figure 25 shows the results for an ISD of 15 km. For the MFN the overall trend in the results is similar to that found in the HPHT simulations. However, it can be seen that the achievable SINR at the worst point in the network is lower than for larger ISDs in the HPHT networks. Again, an improvement in the achievable SINR would be possible by increasing the frequency reuse factor with around a 12 dB improvement from reuse 1 to 3. As with the HPHT network, there is a small gap between reuse 3 and 4.

Regarding the effects in the SFN, it can be seen that the 33 µs and 100 µs CPs still provide limited performance compared with the longer variants. The 200 us CP provides the same SINR as the longer 300 and 400 µs CP, and for this network configuration, increasing the CP would not provide any significant SINR improvement.

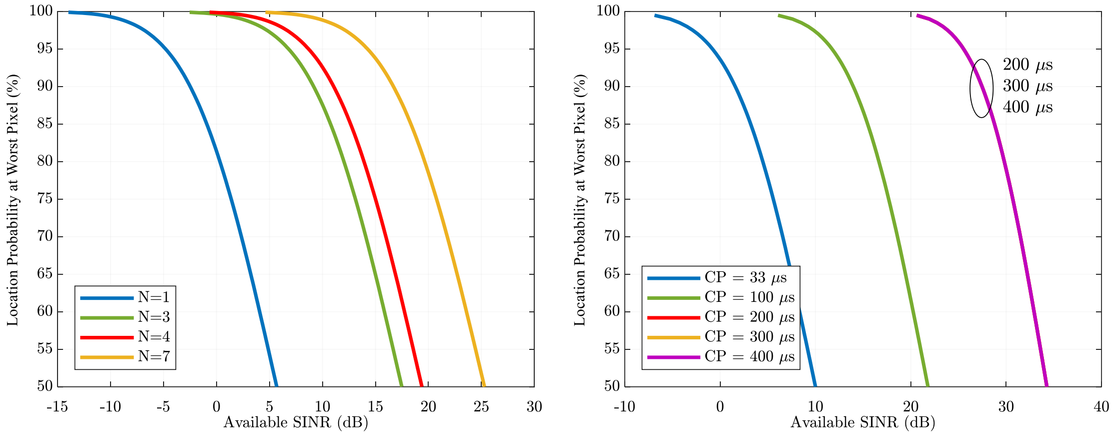

Figure 25: Available SINR as a function of location probability for different CP duration in LPLT MFN (left) and SFN (right) test environment with 15 km ISD.

The analysis of the available spectral efficiency as a function of the ISD reveals that the MFN provides an almost constant trend. There is, however more variation in the SFN. A significantly higher SINR would be possible in networks with shorter ISDs (e.g. 5 to 10 km) with a shorter CP duration (if 100 µs). On the other hand, increasing ISD causes a dramatic impact in SINR. Again, the 200 µs CP duration is considered to be sufficiently long for ISDs between 5 and 20 km as longer CP durations would not improve performance.

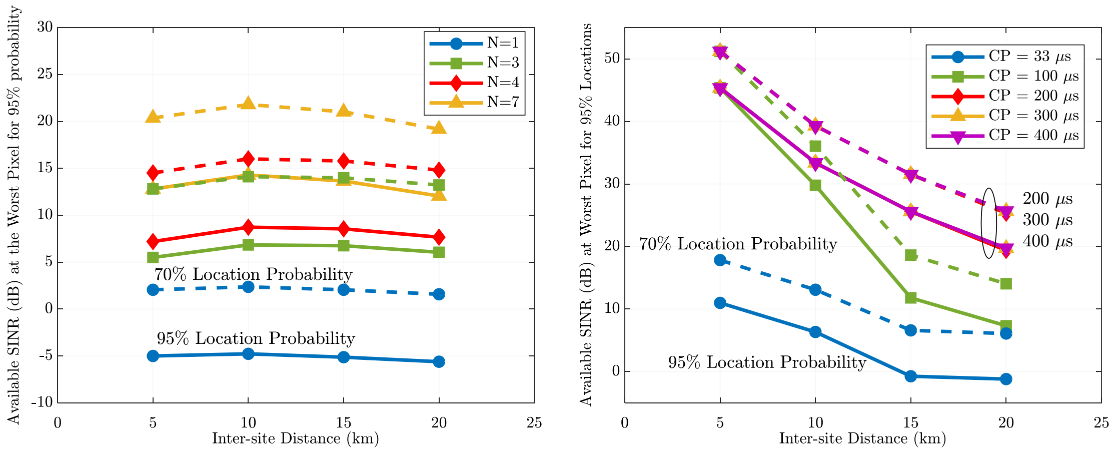

Figure 26: Available SINR at the worst pixel of the LPLT network as a function of the ISD for different frequency reuse factors (MFN) and different CP duration (SFN) (right).

4.4.4.1.3.1 Impact of the Equalization Interval and Overheads

As explained earlier, the coverage performance of the SFN does not only depend on the CP duration but also on the equalization interval, which itself depends on the pilot pattern and the ODFM symbol duration. The following figures show the available SINR as a function of the OFDM symbol duration for different CP durations. It can be seen that the coverage of the network increases when increasing the symbol duration (T_S). This reveals the advantage of increasing the overall OFDM symbol length while keeping the CP duration thanks to a larger equalization interval.

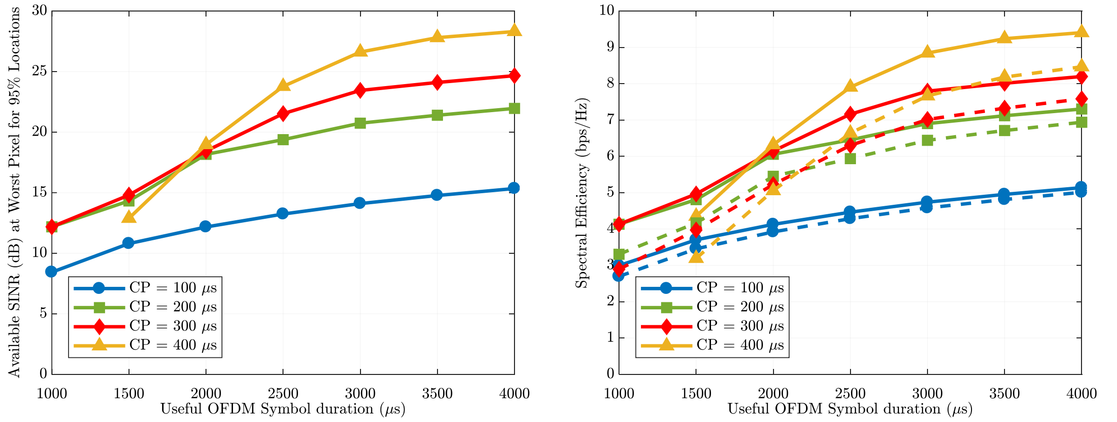

Figure 27: Available SINR at the worst pixel for 95% locations in the HPHT test environment as a function of the CP and T_U durations. Corresponding spectral efficiency (Shannon) – straight lines – and also taking into account CP overhead – dashed lines - (right).

The overhead penalty due to the CP is considered in Figure 27. It can be seen that the overhead decreases when increasing T_S for a given CP duration. In this sense, it can be seen that the same spectral efficiency is obtained with a 400 µs CP and 2000 ms T_S (i.e. 20% overhead) as with 200 µs CP but 2000 ms T_S, which represents 10% overhead.

In order to address this effect from a technology perspective, the following figure shows the location probability for the worst pixel as a function of the available SINR for the eMBMS system configured with 200 µs and T_S 1000 µs (as per Rel' 14) and ATSC 3.0, configured with the most similar CP duration (224 µs) but with T_S 4740 µs (obtained with the combination of 6 MHz carrier bandwidth and a 32k FFT). The result reveals a difference of about 10 dB between eMBMS and ATSC 3.0 just because of the larger OFDM symbol duration. As a reference case, the coverage performance of the MFN with frequency reuse 3 has also been added to the figure.

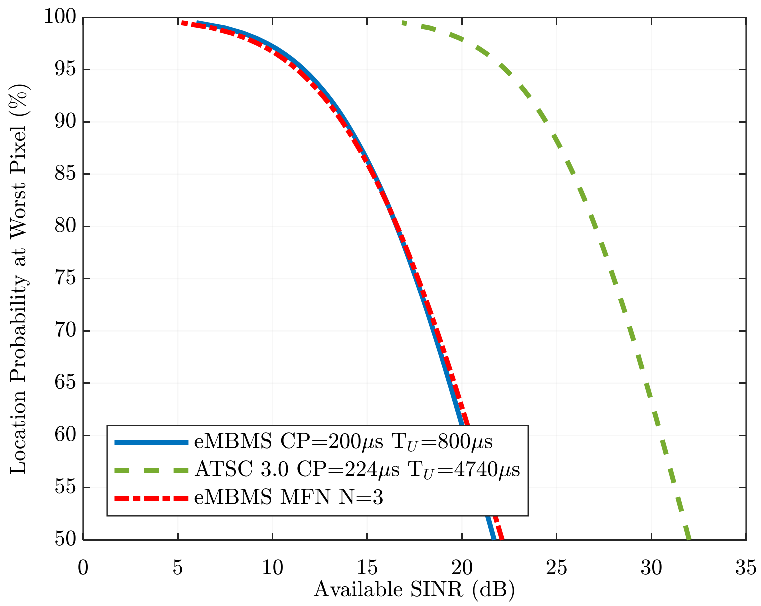

Figure 28: Available SINR for different location probability a the worst pixel of the HPHT MFN and SFN networks for LTE and ATSC 3.0 systems.

The results show that the performance in terms of coverage of LTE Rel' 14 using the CP 200 µs or an MFN implementation with the default CP of LTE lead to the same performance. From the point of view of the spectral efficiency the SFN configuration results in 20% overhead whereas the overhead in the MFN mode is 6.5%. Therefore, it may result more efficient to deploy the system in MFN instead of SFN.

4.4.4.1.3.2 The border effect between neighbouring SFN networks

Users at the border of an SFN area may suffer high levels of interference from adjacent co-channel cells which are not part of the wanted SFN and transmit different content.

The way the problem is addressed in terrestrial broadcasting and cellular networks is different. In terrestrial broadcast networks, interference at borders between different SFNs is often avoided in terrestrial broadcast networks by adopting a frequency reuse of three or more. The use of a reuse factor greater than 1 ensures that adjacent SFN areas do not interfere with each other.

The nominal implementation of frequency reuse 1 in cellular deployments requires eMBMS to use a different interference mitigation strategy. In order to reduce the interferences, cells outside the MBSFN area are configured as reserved cells in which system discovery information is not transmitted. Users in these cells are not able to know about the availability of the service due to the lack of signalling. These reserved cells can serve as guard zones against interference from other cells. Although this strategy is effective at avoiding interference, it has the penalty that it is not possible to use the physical radio resources in the reserved cells, and therefore the capacity in these cells is much reduced. The resources can only be used again for another MBSFN or unicast data at a certain re-use distance. Reserved cells can be configured to transmit the same eMBMS information so that they contribute to enhance the coverage at cell borders, but this is at the expense of increasing the distance from which the physical resources can be employed for transmission. Figure 29 shows an illustrative example of the effect of increasing the number of reserved cells tiers in-between two SFNs.

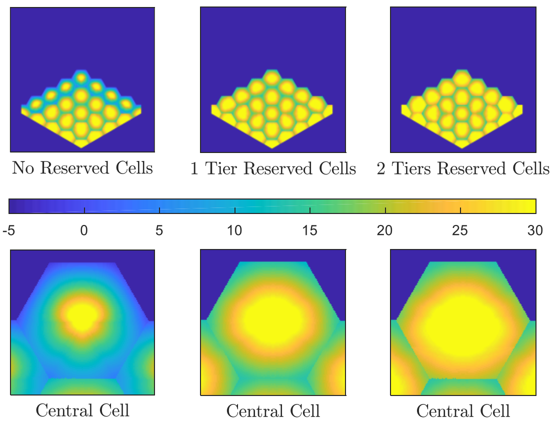

Figure 29: Interference mitigation at cell borders by means of using Reserved Cells between different SFN areas

Figure 30 presents the evaluation of the effect of disabling tiers of cells at the SFN area in comparison with SFN clusters and MFN with frequency reuse 3 and 4. Results are presented for roof-top reception and HPHT and LPLT deployments over a range of ISDs. The left-hand part shows that whereas an SFN presents a large SINR when only SFN self-interference is considered, the performance at the cell border (No Reserved Cells) presents an SINR below 0 dB, in practice this translates in a loss of coverage at the border of the SFN area. By establishing reserved cell tiers, the SINR at the border of the area can be improved. On the other hand, the presence of SFN self-interference for certain ISD values reveal that it may result more efficient to plan the SFN network on the basis of an MFN with multiple SFN clusters adapted to the corresponding CP duration.

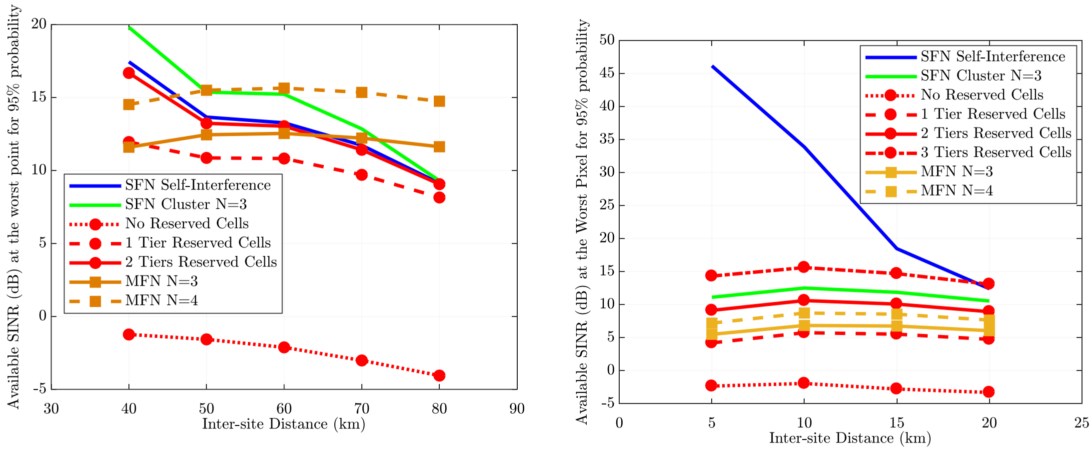

Figure 30: Interference mitigation at cell borders by means of using Reserved Cells between different SFN areas

Note also that the use of reserved-cells would always result in a loss of coverage in such reserved cells unless a different frequency is used. The latter case would lead again to the application of a certain frequency reuse.

4.4.4.1.4 System Discovery and Synchronization

Broadcast systems require of system discovery and synchronization mechanisms so that a receiver can identify the signals and services available in an RF carrier.

4.4.4.1.5 eMBMS Rel'14

LTE system information (SI) is transmitted in the broadcast control (BCCH) logical channel. Generally, BCCH messages are carried on the downlink shared channel (DL-SCH) and transmitted on the PDSCH. This is done in conjunction with a downlink control information (DCI) message transmitted on the physical downlink control channel (PDCCH) that indicates the format and resource allocation of the PDSCH transmission. SI-RNTI, the radio network temporary identity (RNTI) of the system information, scrambles this DCI message. The exception is that some initial system information is conveyed in the master information block (MIB), which is carried on the BCH transport channel and transmitted on the physical broadcast channel (PBCH).

Rel' 14 defines a new mode with 100% resource allocation for MBSFN operation. Due to backward compatibility issues, the acquisition and synchronization of the MBSFN frames require the introduction of a non-MBSFN region occupying part of the first MBSFN sub-frame. This part is known as CAS. The CAS supports PSS, SSS, CRS, PBCH, PDCCH, PDSCH (SI). Therefore, the correct reception of these enables the access to the MBSFN subframe containing the data. Note that the CAS is transmitted using 15 kHz unicast numerology which is different to the numerology employed for the MBSFN subframe (1.25 kHz).

The evaluation of the CAS has been carried out in 3GPP [47], [48]. The PSS/SSS performance is found to be similar as with legacy acquisition (pre-Rel' 14) with a 90% probability of successful acquisition time over an 80 ms period (ie. 8 frames) in a reception environment with -5 dB SINR. The PBCH, PDCCH and PDSCH performance is provided in [48] for the ETU1 (Extended Typical Urban model) and EPA1 (Extended

Pedestrian A model) channel models and antenna configuration 2Tx-2Rx – i.e. a MIMO channel. The target BLER is 1%.

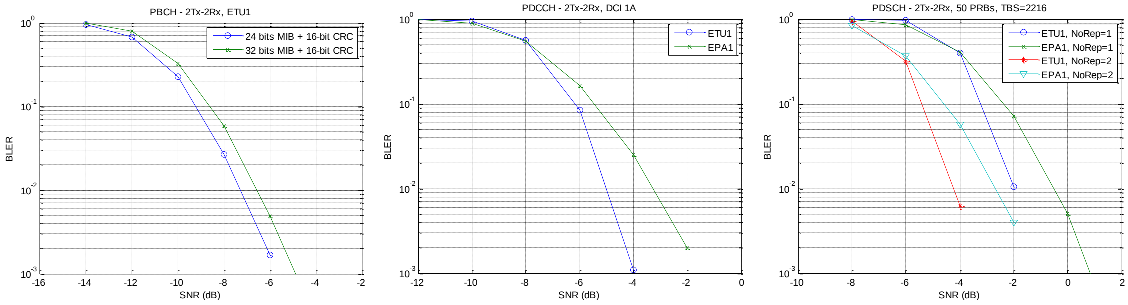

Figure 31: PBCH, PDCCH and PDSCH performance [48]

The outcome of the analysis presents that the required SNRs for 1% PBCH BLER point are -6.6 dB and -4.8 dB for ETU1 and EPA1 channels respectively. The required SNRs for 1% PDCCH (DCI 1A) BLER point are -5.0 dB and -3.3 dB for ETU1 and EPA1 channels respectively. The required SNRs for 1% PDSCH (TBS 1384 bits) BLER point are -5.6 dB and -4.1 dB for ETU1 and EPA1 channels respectively.

Note that results above are for a MIMO channel. Results for SISO are not available. This limitation prevents the correct evaluation of the CAS under likely eMBMS reception conditions in which only one transmitting and receiving antenna port would be used. Therefore, some degree of degradation from the above results should be expected in such networks. Moreover, the Rel' 14 specification does not provide information on whether the content of the CAS can be replicated in different cells within the same SFN.

4.4.4.1.6 ATSC 3.0

In ATSC 3.0 a bootstrap is used to enable service discovery and signalling reception at low signal levels [49]. The bootstrap signal consists of several specially-coded OFDM symbols. The first bootstrap symbol is used for detection, synchronization, and service discovery. The remaining symbols convey system parameters describing the associated physical layer frame structure, e.g., signal bandwidth, sampling rate. The originating sequence for bootstrap signalling is a combination of a Zadoff–Chu sequence and a pseudo-noise sequence in the frequency domain. Signalling information is conveyed through the use of cyclic shifts in the time domain. The coarse timing synchronization, symbol detection, and fractional frequency offset estimation are performed simultaneously in the time domain, while the integral frequency offset estimation and the transmission parameter signalling decoding are performed in the frequency domain. Superior detection and decoding performance are proved by simulation in typical use cases, and very low thresholds and capability in difficult channel models are enabled by the use of the bootstrap.

Below, the performance of the CAS is assessed in the LPLT and HPHT networks previously considered in this document. For these networks the coverage probability as a function of the available SINR has been calculated for two scenarios: the best and worst cases. In the worst case scenario, the reception of the CAS has been considered in a reuse 1 situation where all information contained in the CAS is different from one cell to another. The best case assumes that the CAS can form an SFN with a 16.67 us CP. In this case the CAS is transmitted with the same content in the SFN cells and with unicast numerology using the extended cyclic prefix.

Table 15: Bootstrap Detection Threshold in Different Channel Conditions [49].

TABLE III
SNR THRESHOLD IN DIFFERENT CHANNEL CONDITIONS

Channel conditions	AWGN		TU6 (f_d in Hz)		Mobile SFN	6SFN	6MFN
	CFO&SFO	Non-CFO&SFO	129Hz	39Hz	two-path TU6		
Detection threshold(dB)	-15.78	-16.12	-8.73	-8.76	-9.63	-11.61	-14.45
Decoding threshold(dB)	-15.77	-16.08	-8.71	-8.74	-9.62	-11.48	-14.45
Channel conditions	0dB echo (Delay, Phase shift)				Pedestrian channel		
	(1024samples,0)	(1024samples,pi)	(532us,0)	(532us,pi)	indoor	outdoor	
Detection threshold(dB)	-15.13	-15.00	-13.81	-13.82	-9.73	-10.57	
Decoding threshold(dB)	-12.91	-12.73	-13.72	-13.74	-9.74	-10.52	

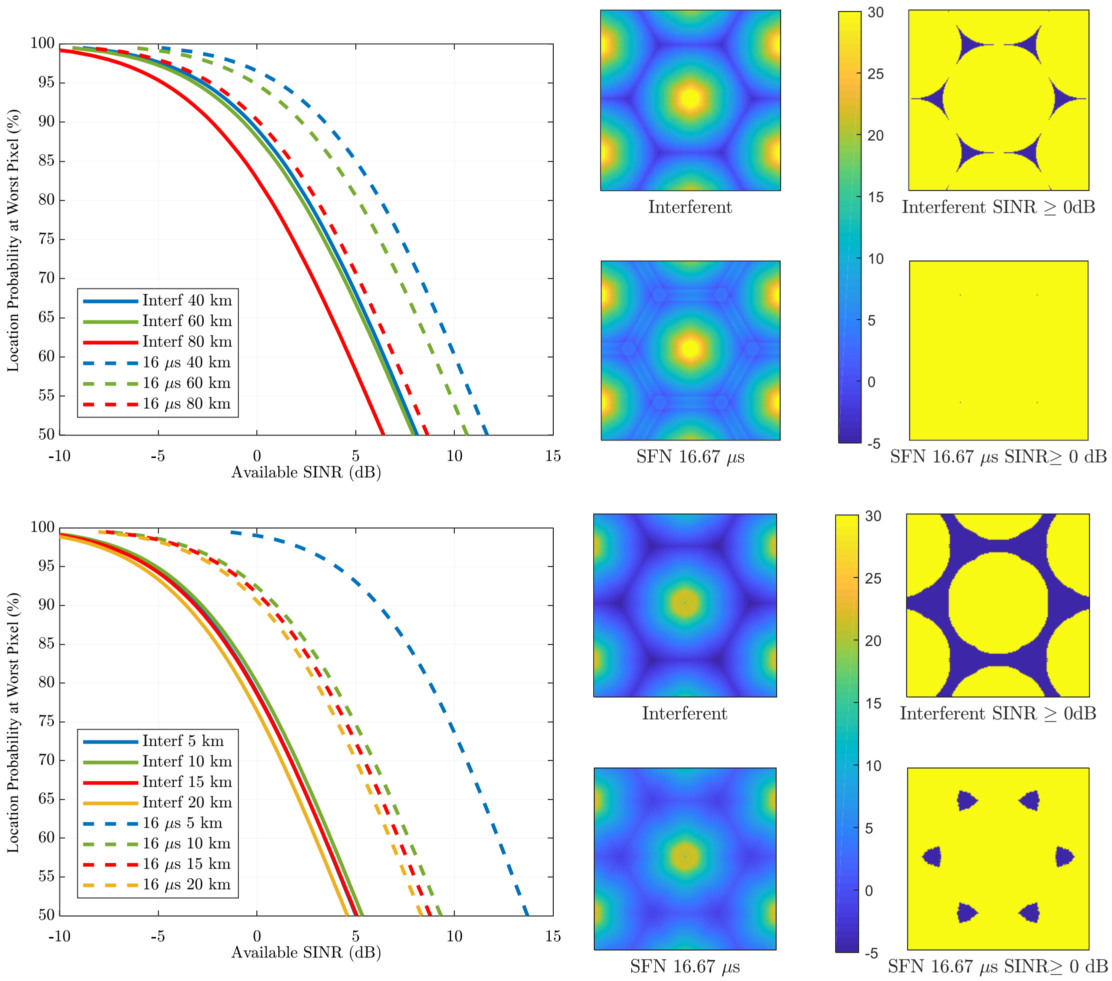

Figure 32: Available SINR for the CAS for different location probabilities at the worst pixel. The CAS is modelled as a fully interfering subframe between different cells in the SFN area (Interf) or as a subframe with unicast numerology (16 us).

The result show that the CAS, as defined in Rel' 14, may limit the coverage of the system as soon as certain areas would provide an available SINR below the threshold of the CAS.

The coverage of eMBMS in a national SFN is now assessed in the UK DTT network in order see what may happen in a more practical setting. In this example the UK Prediction Model (UKPM) was used – a prediction model jointly developed by ITC, BBC, Crown Castle and NTL for planning DTT services in the UK. All 1,100+ UK DTT transmitters were modelled with the eMBMS parameters shown in Table 16. All other physical characteristics of the network, such as antenna patterns, ERPs, transmitter locations and antenna heights were otherwise unchanged. The predicted coverage is shown in the next table where the CAS & MBSFN row shows where these two signals would be available from the same site. A target SINR of at least 20dB was used for the MBSFN as more than 98.5% of the UK population may receive this level today.

Figure 33: Populated pixels in UK where reception of either CAS-only (red), MBSFN-only (blue) or both (green) is possible.

Table 16: UKPM Results

	Percentage of UK Households at Percentage Locations MBSFN: CP 200 µs, Ts 1 ms, EI 267 µs	
	70%	**95%**
CAS (-3 dB)	100	98.6
MBSFN (20 dB)	86.5	67.4
CAS & MBSFN	86.5	66.5

4.4.4.1.7 Coverage Analysis under different Test Environments

Figure 34 and Figure 35 show a summary of the available SNR in dBs for LPLT and HPHT networks in different environments with network layout, receiving conditions, propagation models and coverage criteria as detailed in Annex A.4.

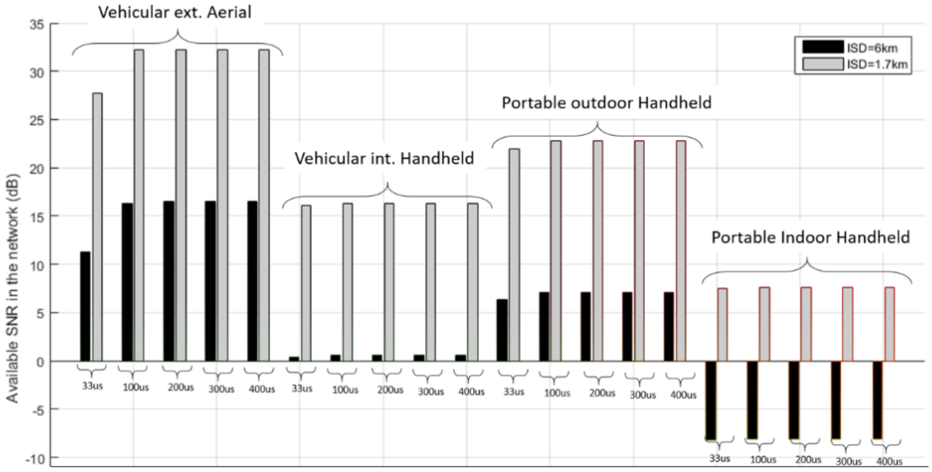

Figure 34: Summary of available SNR in dB for LPLT (rural) networks in vehicular external aerial, vehicular internal handheld, portable outdoor and portable indoor environments for 95% location probability. Parameters defined in Annex A.4.

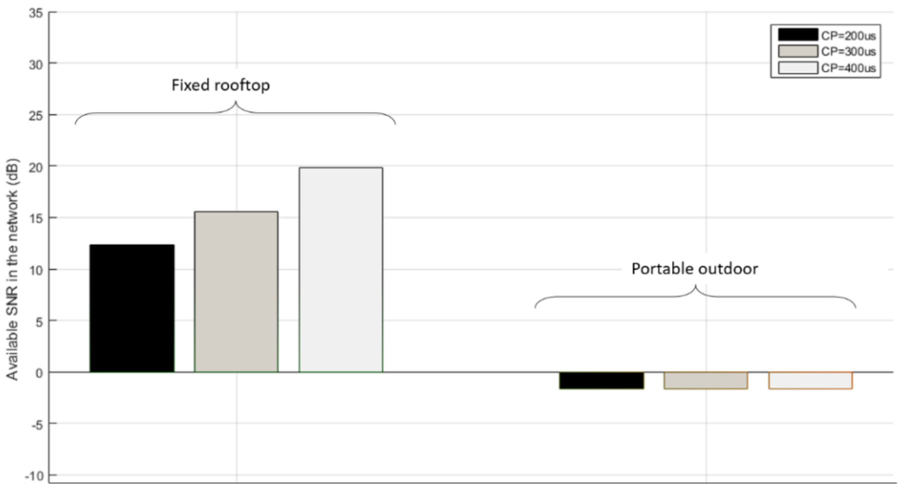

Figure 35: Summary of available SNR in dB for HPHT networks in fixed rooftop and portable outdoor environment and for 95% location probability. Parameters defined in Annex A.4 configuration HPHT1.

4.4.5 System-Level Simulations

4.4.5.1 User spectral efficiency

The user spectral efficiency, as discussed in section 4.3.3.3.1, is calculated as the rate normalized with respect to the service time and carrier bandwidth, for a single-layer configuration with the assumption of full-buffer traffic model.

Figure 36 shows the CDF of user spectral efficiency, denoted by user SE in b/s/Hz, for the urban scenario with user density of 10, 20, 30, and 40 UEs per cell with 100% indoor distribution of users. The assumed transmission scheme here is unicast; assuming 100% indoor distribution of users. As expected, the user spectral efficiency with lower density of users, e.g., 10 UEs per cells, is higher than that of higher density of users. The major reason is that with higher density of users the allocated radio resources per user decrease, leading to a lower user spectral efficiency.

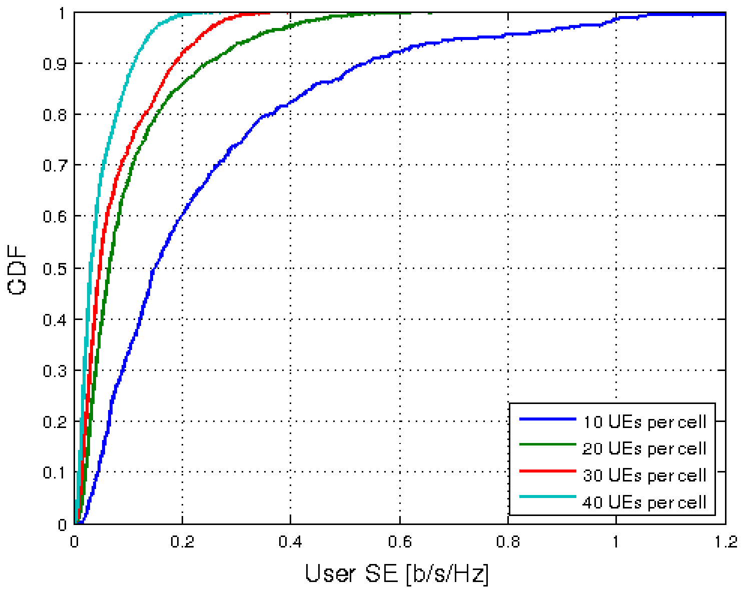

Figure 36: CDF of user spectral efficiency, denoted by user SE in b/s/Hz, for the urban scenario with user density of 10, 20, 30, and 40 UEs per cell.

Figure 37 shows the average and 5-%ile user spectral efficiencies for various densities of users based on the CDF plot in Figure 36. Accordingly, both the average and 5-%ile user spectral efficiencies decrease with the increase of the density of users.

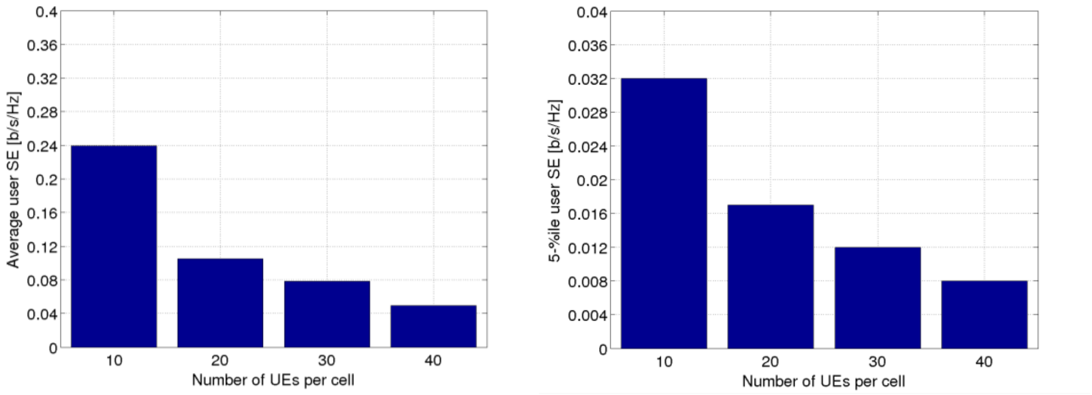

Figure 37: The average and 5-%ile user spectral efficiencies for various densities of users based on the CDF plot

Table 17 shows the average and 5-%ile user spectral efficiencies for urban scenario with 100% distribution of outdoor users, for various user densities. Similarly, the trend of performance evaluation shows that both the average and 5-%ile user spectral efficiencies decrease with the increase of the density of users.

Table 17: The average and 5-%ile spectral efficiencies for urban scenario with 100% distribution of outdoor users, for various density of user distribution.

Number of UEs per cell	Average user SE [b/s/Hz]	5-%ile user SE [b/s/Hz]
10	0.234	0.045
20	0.126	0.022
30	0.089	0.015
40	0.058	0.009

Comparing the performance of the indoor urban case in Figure 37 and outdoor urban case in Table 17, it is observed that there is no significant difference between the indoor and outdoor cases in terms of 5-%ile and average user spectral efficiencies. The main reason is that the variation of penetration loss in indoor and outdoor cases plays a lower role in the variation of the signal quality in the urban case which is predominantly interference limited scenario.

Table 18 summarizes the average and 5-%ile spectral efficiencies for rural 100% indoor and 100% outdoor distribution of users densities. In this case, both the average and 5-%ile spectral efficiencies exhibit an improved performance for the outdoor rural case as compared to the indoor rural. Unlike the urban case, the variation in the level of penetration loss in indoor and outdoor cases play a significant role in the variation of signal quality in the rural case, which is predominantly noise-limited scenario.

Table 18: The average and 5-%ile spectral efficiencies for rural 100% indoor and 100% outdoor distribution of users for sample density of 10 and 20 UEs per cell.

Scenario	Average SE (b/s/Hz)	5-%ile SE (b/s/Hz)
100% indoor with 10 UEs per cell	0.289	0.017
100% indoor with 20 UEs per cell	0.144	0.009
100% indoor with 30 UEs per cell	0.094	0.006
100% indoor with 40 UEs per cell	0.076	0,006
100% outdoor with 10 UEs per cell	0.386	0.047
100% outdoor with 20 UEs per cell	0.188	0.022
100% outdoor with 30 UEs per cell	0.123	0.015
100% outdoor with 40 UEs per cell	0.09	0.011

In addition to urban and rural scenarios, indoor hot spot scenarios are evaluated based on the simulation configuration described in Annex A, for which the network deployment is depicted in Figure 38. Herein, the access points are deployed with ISD of 20m in an office floor with 120m x 50m dimension.

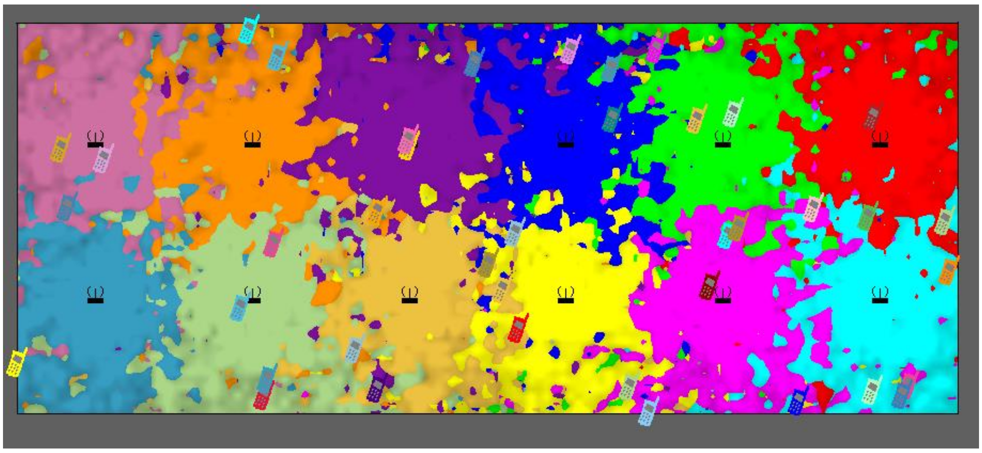

Figure 38: Network deployment and cell layout for indoor hotspot scenario.

Figure 39 shows the average and 5-%ile user spectral efficiencies for sample user density of 40, 50, 60, and 70 UEs over the office floor. Herein, both the average and 5-%ile user spectral efficiencies decrease with increase of density of users.

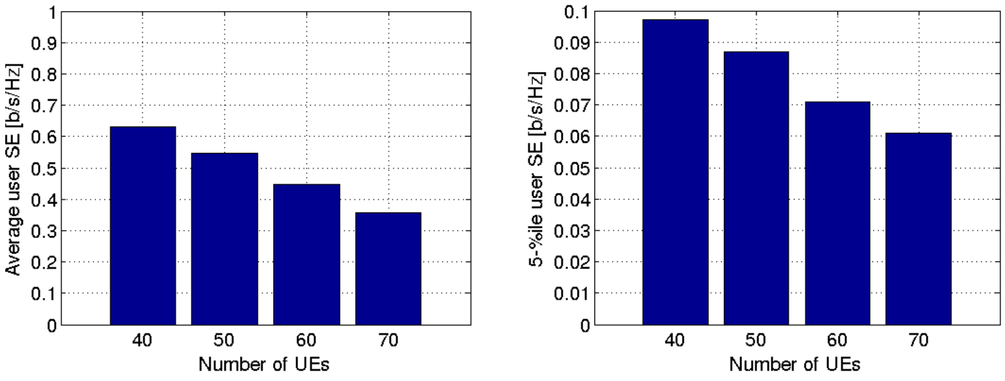

Figure 39: The average and 5-%ile user spectral efficiencies for sample user density of 40, 50, 60, and 70 UEs over the office floor.

So far, the user spectral efficiencies of a unicast LTE-A pro settings have been reported. The RLC layer packet loss rate thereof is negligible as unicast uses link adaptation and HARQ to resolve packet loss. On the other hand, SC-PTM does not use link adaptation and HARQ, leading to packet loss rates. Hence, the user spectral efficiencies as well as the packet loss rate are analysed as follows by using the system level simulation for SC-PTM.

Figure 40 to Figure 44 show the average spectral efficiency and the CDF of packet loss rate for various MCS settings in scenarios of urban 100% indoor, urban 100% outdoor, rural 100% indoor, rural 100% outdoor and indoor hotspots, respectively. The considered sample MCS settings 0, 1, 2, and 3 represent QPSK modulation with code rate of 0.0945, 0.1225, 0.1541 and 0.1996 respectively. With higher MCS setting, it is shown that the average SE increases with the use of higher MCS setting. However, the packet loss rate considerably increases with use of higher MCS settings. Selection of proper MCS setting should take into account the packet loss rate requirement of the supported applications. For example, if we want to support 95 % of the users with packet loss 10^{-3}, then one can use MCS settings 0 and 1 in the urban 100% indoor and 100% outdoor case. On the other hand, MCS settings 0, 1 and 2 can support the aforementioned packet loss rate in the rural 100% indoor and 100% outdoor scenarios. Moreover, the evaluation for indoor hotspot shows that there is very high packet loss rate due to strong interference.

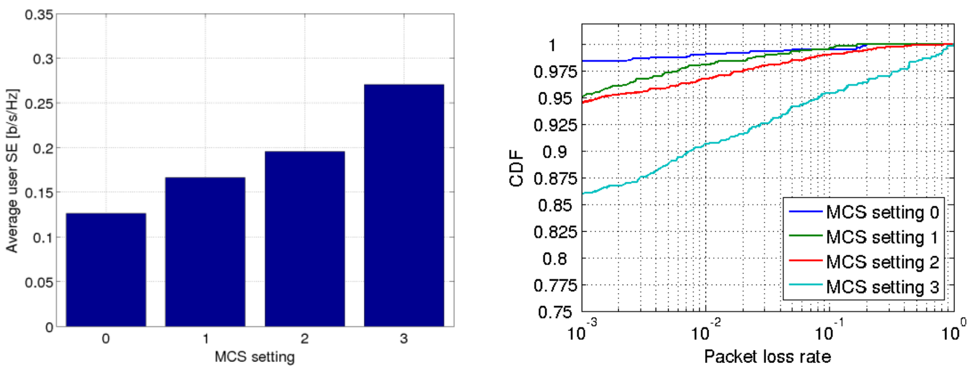

Figure 40: Average user spectral efficiency and CDF of packet loss rate in urban 100% indoor

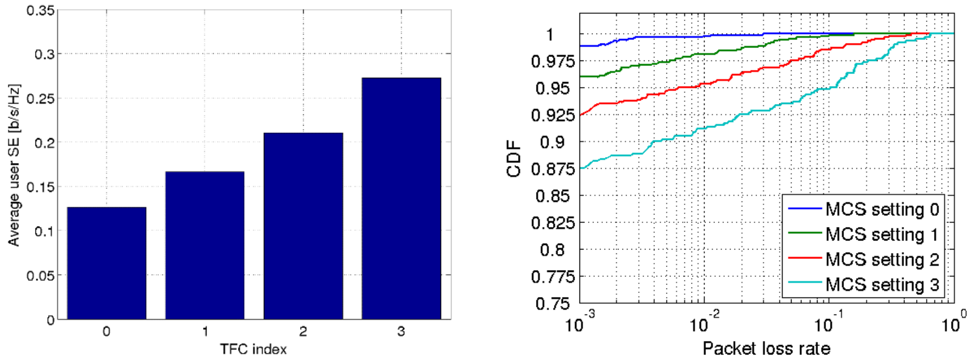

Figure 41: Average user spectral efficiency and CDF of packet loss rate in urban 100% outdoor.

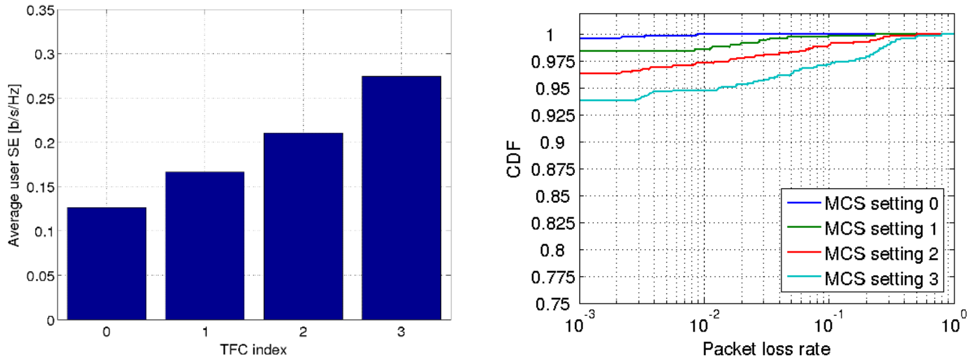

Figure 42: Average user spectral efficiency and CDF of packet loss rate in rural 100% indoor

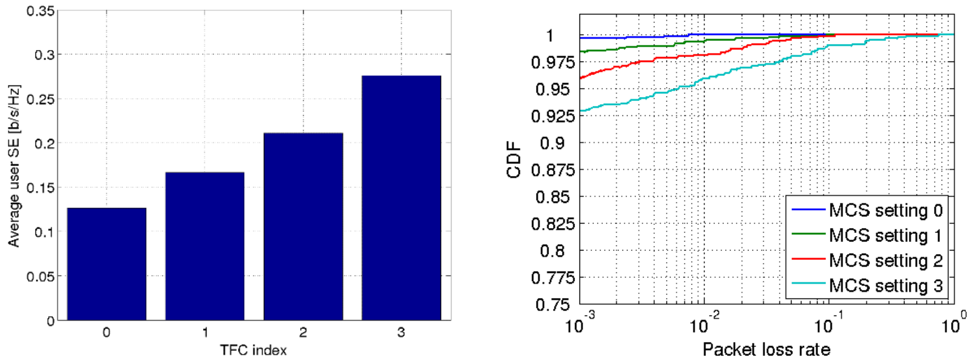

Figure 43: Average user spectral efficiency and CDF of packet loss rate in rural 100% outdoor

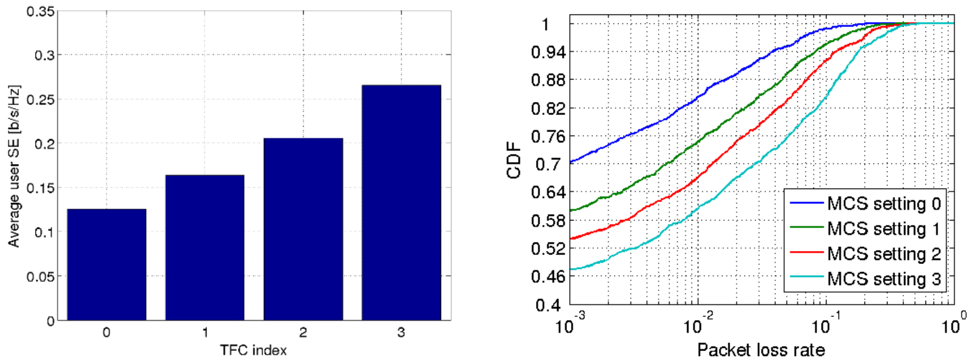

Figure 44: Average user spectral efficiency and CDF of packet loss rate in indoor hotspot

4.4.5.2 Average cell spectral efficiency

This subsection presents the average cell spectral efficiency of LTE-A pro unicast technology for various scenarios based on the system level simulation.

Table 19 and Table 20 summarize the average cell spectral efficiencies for urban and rural scenarios, respectively for the sample user density of 10 UEs per cell in the 100% indoor and 100% outdoor cases. The evaluation in the urban scenario does not show significance difference between indoor and outdoor cases. On the other hand, in the evaluation for rural cases, the average cell spectral efficiencies for the outdoor scenarios are higher as compared to their respective indoor case because the penetration loss in indoor scenarios plays a considerable role on the signal quality in a rural environment which is predominantly noise limited.

Table 19: Average cell spectral efficiency (SE) for indoor and outdoor urban scenario for sample user densities of 10 and 20 UEs per cell.

Scenario	Average Cell SE [b/s/Hz]
100% indoor with 10 UEs per cell	2.393
100% outdoor with 10 UEs per cell	2.337

Table 20: Average cell spectral efficiency (SE) for indoor and outdoor rural scenario for sample user densities of 10 and 20 UEs per cell.

Scenario	Average Cell SE [b/s/Hz]
100% indoor with 10 UEs per cell	2.865
100% outdoor with 10 UEs per cell	3.85

Table 21 shows the average cell spectral efficiency for indoor hotspot scenario in an office floor of 120m x 50m dimension for sample user density of 40, 50, 60 and 70 UEs over the floor. Herein, it is shown that there is no significance variation in average cell spectral efficiency for various user densities.

Table 21: Average cell spectral efficiency (SE) in indoor hotspot scenario for sample user densities 40, 50, 60 and 70 over the office floor.

Scenario	Average Cell SE [b/s/Hz]
40 UEs	2.184
50 UEs	2.287
60 UEs	2.266
70 UEs	2.074

Figure 45 shows the user spectral efficiency, the average and 5-%ile user spectral efficiencies for a unicast transmission mode and average user spectral efficiency for the SC-PTM transmission. The unicast transmission mode uses adaptive MCS scheme with support of HARQ, the SC-PTM transmission mode uses fixed MCS settings that fulfil the criteria that 95% of the users have packet loss lower than 10^{-3}. The average spectral efficiency in SC-PTM applies as a performance measure for the cell edge users as well because SC-PTM uses a fixed MCS setting for all users in the network. The comparison is shown for urban 100% indoor users, urban 100% outdoor, rural 100% indoor and rural 100% outdoor scenarios. In these evaluations the CDF of packet latencies has not been calculated (which could be useful to benchmark latency requirements) since the simulation have been performed under the full buffer assumption and to obtain representative latency calculations more realistic traffic models need to be used.

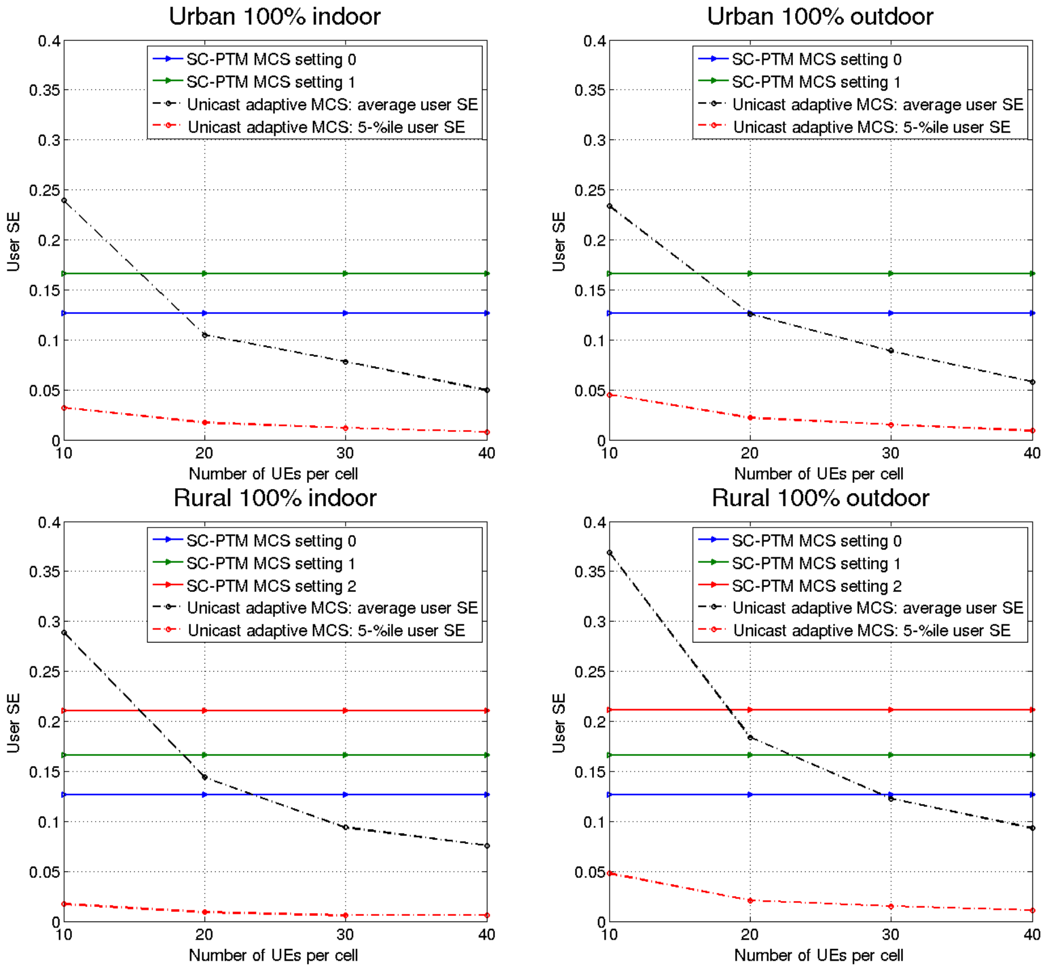

Figure 45: Comparison of SC-PTM and Unicast for eMBB dense urban and rural test environments.

5 Summary and Conclusions

5.1 Summary on 5G-Xcast RAN Technical Requirements

This report has defined technical requirements for the WP3 on Radio Access Network derived from the high-level requirements in WP2 D2.1. This covers the four vertical sectors: Media & Entertainment, Public Warning, Automotive, and Internet of Things along with their respective use cases [21]. A detailed list of requirements to each of the use cases can be found in Chapter 2.

To fulfil the identified requirements, the 5G-Xcast RAN solution should provide a flexible and optimized RAN that is able to adapt to the specific constrains of the relevant four vertical sectors in this project. In particular, the 5G-Xcast RAN should allow optimising radio resources and providing further interactivity through enhanced PTM (broadcast/multicast) transmissions and feedback mechanisms from the users. The RAN solution should provide flexibility on the available waveform parameters (OFDM parameters such as cyclic prefix / CP and inter-carrier spacing) to allow deployments in different types of network deployments such as HPHT and LPLT networks. This flexibility in the type of networks would allow the system to efficiently use the best network to provide better coverage in different environments, for example, coverage to indoor, outdoor and vehicles.

A flexible RAN would also facilitate the orchestration of the network to provide seamless experience when the users move across environments. With the increase in the quality of video formats (e.g., UHDTV) and new experiences such as Virtual Reality broadcast, the new RAN requires a significantly improved spectral efficiency from both the physical layer (i.e., advanced signal processing algorithms and use of MIMO) and from the network deployment point of view (i.e., efficient use of frequency reuse).

A key component of the 5G-Xcast RAN is the efficient multiplexing of PTP and PTM transmissions, certainly as most of the identified use cases in WP2 have a combination of broadcast/multicast and unicast transmissions. An efficient multiplexing of PTP and PTM in the same frequency band as well as the ability to switch between each can unlock the potential of the use cases identified in WP2. It is also important that the integration of PTM transmissions does not pose significant changes to the radio air interface, nor to the radio technology protocols to facilitate the integration of PTM transmissions in 5G.

New use cases such as VR broadcast and remote live production require Gbps communications and low latency. Furthermore, they may require the use of new frequency bands with wide bandwidth allocations as well as the use of MIMO. The 5G-Xcast RAN solution should not be restrictive on the type of frequency bands to allow these types of use cases. On the other hand, PW and IoT use cases require significantly less data rates than the previous aforementioned data hungry cases. However, they instead require high reliability and low energy consumption that the 5G-RAN solution must to be able to support through the frame structure configuration.

5.2 Conclusions from RAN benchmark of technical KPIs

In this report, the selection of KPIs and evaluation methodology for the RAN benchmark in WP3 has been aligned with the ITU-R IMT-2020 RIT evaluation process [18]. Initially, the 5G-Xcast project selected relevant KPIs for the use cases from those defined in [18]. IMT-2020 defines three usage scenarios: eMBB, URLLC and mMTC. Although WP3 will cover these across the course of the project, this report has focused on the eMBB usage scenario, which is representative of the most relevant use cases identified in WP2 [21]. The selection of the KPIs has considered both PTP and PTM transmission modes since most of the relevant use cases identified in WP2 [21] use a combination unicast and multicast/broadcast components. The KPIs listed in [18] are focused on PTP. Hence, additional complementary KPIs (together with its evaluation methodology) have been defined to better assess specific aspects of PTM scenarios.

All KPIs have been individually evaluated through analytical, inspection or simulation procedures specific and relevant to the KPI in question. The selected test environments are representative of the WP2 use cases and are also aligned to those defined in the IMT-2020 evaluation guidelines.

The main target in the KPI performance evaluation has been the technical specification 3GPP Rel'14 LTE-Advanced-Pro specification for both PTP and PTM transmission modes. For PTM this specification defines SC-PTM and MBSFN under the eMBMS umbrella. This is subsequently compared to the state of the art ATSC 3.0 specification.

The following subsections summarise the main findings of the RAN benchmark in this deliverable.

5.2.1 Inspection and Analytical Evaluation

In the inspection and analytical evaluation category, the following KPIs have been considered: bandwidth, peak BICM spectral efficiency, peak data rate and peak spectral efficiency.

While ATSC 3.0 only provides a single 6 MHz bandwidth allocation (that can be extended to 12 MHz using 2 RF carriers), LTE provides a wider set of possible bandwidth allocations ranging from 1.4 to 20 MHz. Additional carrier aggregation of 5 RF carriers can increase the total bandwidth to 100 MHz. However, higher bandwidth allocations may be required to cope with very high data rate use cases such as virtual reality broadcast (cf. Chapter 2).

A comparison of the peak BICM spectral efficiency between ATSC 3.0, SC-PTM and MBSFN (cf. Table 4) shows that without the use of MIMO, ATSC 3.0 provides the highest BICM spectral efficiency with 10.36 bpc (bits per cell), due to use of high order constellations with 4096 symbols. The SISO peak BICM spectral efficiency for SC-PTM and MBSFN (carrier spacing of 15 kHz) is 7.09 and 7.06 bpc, respectively. If MIMO is employed (multiple independent data streams across transmit antennas) SC-PTM with 4 spatial streams (MIMO 4x4) can reach up to 28.36 bpc. It is worth pointing out that MBSFN is limited to 7.06 bpc since the use of MIMO it is not specified. ATSC 3.0 allows 2x2 MIMO and the peak BICM spectral efficiency is thus increased to 20.72 bpc.

The previous KPI did not include the different overheads due to synchronisation, frequency guard bands, CP, etc. The peak spectral efficiency takes into account these overheads. In this case without MIMO, ATSC 3.0, SC-PTM and MBSFN provide 9.78, 4.89 and 4.13 bits/s/Hz, respectively. This corresponds to a reduction in spectral efficiency due to overheads of 5.6%, 30.9% and 41.5%. In the MIMO case, the peak spectral efficiency for ATSC 3.0 is 19.56 bits/s/Hz (MIMO 2x2) and SC-PTM is 19.58 bits/s/Hz (MIMO 4x4), which corresponds to a reduction due to overheads of 5.6% and 30.9%.

Regarding peak data rate (including overheads), ATSC 3.0 is able to deliver in one RF carrier 58.70 Mbps without MIMO and 117.3 Mbps with 2x2 MIMO. SC-PTM can deliver 97.9 Mbps (with one RF carrier and without MIMO) and if multiple spatial streams are transmitted the peak rates can be increased to 195.8 Mbps and 391.6 Mbps (in one RF carrier), for MIMO 2x2 and MIMO 4x4, respectively. In this report, the combination of carrier aggregation and MIMO for SC-PTM has not been considered. If carrier aggregation of 5 RF carriers is employed, then the peak data rate for SC-PTM is increased up to 489.5 Mbps. For MBSFN, the overhead due to the transmission of the

CAS needs to be taken into account, slightly reducing the available peak rate to 82.6 Mbps. Note that in this case, the maximum TB size has been reduced from 97896 to 84760.

A summary of the discussed KPIs related to spectral efficiency and data rates are summarised in Table 22.

Table 22: Summary of peak BICM spectral efficiency, peak spectral efficiency, peak data rates and corresponding overheads for PTM technologies MBSFN, SC-PTM and ATSC 3.0.

Technology	Antenna Scheme	Peak BICM spectral efficiency (bpc)	Peak spectral efficiency (bits/s/Hz)	Overhead (%)	Peak data rate (Mbps)
ATSC 3.0	SIMO	10.36	9.78	5.6	58.70
	MIMO 2x2	20.72	19.56	5.6	117.3
SC-PTM	SIMO	7.09	4.89	30.9	97.9
	MIMO 2x2	14.18	9.79	30.9	195.8
	MIMO 4x4	28.36	19.58	30.9	391.6
MBSFN (200µs)	SIMO 1x2	7.06	4.13	41.5	82.6
Note 1: Carrier aggregation is not considered in this table Note 2: schemes named SIMO indicate one independent information stream. Schemes named MIMO 2x2 and MIMO 4x4 indicate 2 and 4 independent information streams, respectively.					

5.2.2 Link-Level Simulations

In this subsection, the findings of link-level simulations to obtain the BICM spectral efficiency and mobility KPIs are summarised. The required CNR (dB) to achieve a BLER of 0.1% for a given BICM spectral efficiency (bpc) has been simulated for multiple channel models. Although a demanding QoS requirement increases the CNR, it ensures a higher probability of successful reception, suitable for PTM transmissions without feedback. The channel models selected for the evaluation are:

- AWGN to study the performance of the modulation and coding schemes;
- MIMO i.i.d. Rayleigh distributed channel with two transmit and receive antennas and ideal cross-polarisation factor (no coupling between antennas), to study the spatial multiplexing gain;
- Fixed rooftop, portable outdoor and portable indoor environments to assess the performance of the different technologies in static environments along with the effect of frequency interleaving.

In AWGN channel, the use of **long code-words with LDPC codes** providegains (ca. 1 dB, see Table 7) at the expense of longer latencies. It is worth pointing that the development of NR has adopted LDPC codes with variable size for the PTP data path and these codes should be the baseline for next evaluations in the following WP3 task, T3.2. Furthermore, the use of **non-uniform constellations** can provide shaping gains, which reduce the CNR up to 1 dB with 256QAM modulations and close the gap with the Shannon theoretical limit. As main drawback, non-uniform constellations adopted in ATSC 3.0 for this modulation order increase the demapping complexity at the receiver, since 1D-demapping cannot be applied.

For the scenarios evaluated, Table 23 summarises of the BICM spectral efficiency gain (dB) of ATSC 3.0 over MBSFN (with 200 µs cyclic prefix) and SC-PTM. Representative CNRs of 20 dB for fixed rooftop and MIMO reception, and 10 dB for portable scenarios have been selected. In all channel models, except MIMO i.i.d. Rayleigh channel model, it is assumed that one transmit and one receive antenna are employed. Although it is commonly assumed that LTE receivers have two receive antennas, one receive antenna has been assumed to study the potential performance improvements of the different signal processing schemes. In the lower UHF frequency band, achieving good de-correlation properties using cross-polar antennas in a smartphone footprint can be challenging. Hence the ability to deploy the use of two receive antennas in this band needs to be confirmed.

Table 23: ATSC 3.0 BICM spectral efficiency gain (bpc) over SC-PTM and MBSFN for the different scenarios considered.

Type of reception	MIMO	Fixed rooftop	Portable outdoor	Portable indoor	Mobile
Representative CNR	19 dB	20 dB	10 dB	10 dB	5 dB
ATSC 3.0 gain over SC-PTM	~1.1 bpc	~0.80 bpc	~0.45 bpc	~0.15 bpc	~0.75 bpc
ATSC 3.0 gain over MBSFN	~3.8 bpc	~0.75 bpc	~0.50 bpc	~0.25 bpc	~0.80 bpc

From Table 23, the following conclusions can be extracted:

- In MIMO i.i.d. Rayleigh channel the use of multiple transmit and receive antennas can provide **spatial multiplexing** gains that provide significant performance improvements at high CNR values. This is a major drawback for MBSFN that does not support MIMO. Comparing ATSC 3.0 and SC-PTM, the former provides better performance by the use of more modern coding and non-uniform constellations.
- Fixed rooftop, portable outdoor and portable indoor environments show that the use of **long code-words** can provide performance improvements.
- The use of **non-uniform constellations** could provide important capacity gains at the expense of an increased demapping complexity.

Regarding the mobility KPI, the performance of MBSFN with the new CP of 200 µs, SC-PTM and ATSC 3.0 are evaluated in the TU6 channel. For ideal channel estimation and 120 km/h (at 700 MHz carrier frequency), the following can be concluded:

- ATSC 3.0 provides capacity gains for a representative CNR of 5 dB, as shown in Table 23. The use of **time interleaving** at the physical layer **in ATSC 3.0 can provide significant gains compared to LTE**. It has been demonstrated that time interleaving depths of 50 ms are sufficient to provide important gains in a wide range of spectral efficiencies.
- **SC-PTM outperforms MBSFN** ($\Delta f = 1.25\ kHz$) in terms of spectral efficiency for mobile scenarios. The use a larger carrier spacing makes easier the demodulation despite the Doppler shift introduced by the channel.
- **MBSFN with AL-FEC enhances the resilience** of the transmission at the expense of reducing the spectral efficiency and increasing the zapping time. AL-FEC coding provides an efficient performance in mobile scenarios with time variability, especially when short TIL is also used at the physical layer. However, AL-FEC is not efficient in scenarios with fixed channels due to the lack of time diversity [30].

For real channel estimation, a wide range of Doppler shifts is evaluated for ATSC 3.0 and MBSFN with subcarrier spacing of 1.25 kHz. In this study, due to the higher subcarrier spacing of 15 kHz, SC-PTM has not been included. Regarding the channel estimation algorithm, a simple Least Square estimator on reference signals, followed by a 2-D linear interpolation in time and frequency domain has been used for all studied configurations, although better performance can be expected with more sophisticated estimation algorithms. From the simulations, the following conclusions can be drawn:

- The use of **time interleaving can increase the maximum speed** that mobile users can tolerate without significant performance degradation.
- The maximum speed tolerable depends on multiple factor such as the target (BICM) spectral efficiency of the system (more robust MCS allow higher maximum speeds). For a BICM spectral efficiency of approximately 2 bpc, **MBSFN designed for large SFN coverage areas cannot tolerate user speeds higher than 100 km/h at 700 MHz**. Although better performance could be expected with more sophisticated estimation algorithms there is still a considerably gap from the 250 km/h requirement from 5G NR mobility broadcast.

Other techniques that have not been evaluated in this report but that could also provide additional improvements are non-orthogonal multiple access (NOMA) [32] and multi-radio-frequency (Multi-RF) channel technologies [33]. Study items regarding NOMA have been carried out in Rel'14 [34], and Rel'15 [35], but its adoption has been postponed. Another variant known as Layered Division Multiplexing (LDM) has been adopted in ATSC 3.0. Gains up to 7 dB compared to TDM for the same service data rate were obtained in [36]. Given the additional improvements these schemes offer, they are certainly viable enablers in the 5G-Xcast RAN solution and should be explored further.

Multi-RF may allow the interleaving of channels across the same or different frequency bands. Time Frequency Slicing (TFS) or Channel Bonding (CB) with SNR averaging may become key technologies, improving transmission robustness and thus efficiency as shown in [37][38]. Although LTE adopted Carrier Aggregation (CA), its feature set is limited and these advance multi-RF techniques should be explored.

5.2.3 Coverage Simulations

The following can be concluded from the analysis based on coverage simulations:

- The **lack of granularity for CP duration in LTE leads to excessive capacity overhead** with respect to DTT (ISD between 10-60 km)
- A **200 µs CP** would theoretically be sufficient to cope with SFN self-interference in HPHT topologies (ISD up to 60 km). However, it **is insufficient in LTE**. The use of a larger CP duration (e.g. 400 µs) may improve the performance.
- The most significant coverage improvement is found when **increasing the OFDM symbol duration**. An increased duration in LTE of 2 ms, with a 200 µs CP would provide similar performance as with 400 µs CP for the same ODFM symbol duration. This also **produces a reduction of capacity overhead** from 20% to 10%.
- The possibility of **introducing finer selection of CP and OFDM symbol durations** that optimize the coverage/capacity trade-off for different network topologies **should be addressed in 5G**.
- In general, **SFN provides a more efficient solution** for coverage extension **than MFN for the same frequency reuse factor**. However, the lack of enough CP could reduce the performance making the use of SFN less attractive due to the larger overhead compared to a mode adapted to MFN.
- **SFNs may become severely interference-limited at the coverage borders.** The option of including reserved cells may increase the coverage performance at the expense of not guaranteeing service continuity between SFN areas. A deployment based on **SFN clusters whose size is adapted to the maximum ISD allowed by the CP duration may prove interesting**. This allows extension

of the service across a large area while decreasing interference at cluster borders as well as SFN self-interference.

- The use of the **CAS with unicast numerology may prevent the proper deployment of SFN areas** since, under certain circumstances, the coverage area may become limited by the CAS whereas the MBSFN subframe could potentially be received. The possibility of **sending the initial signalling in SFN** mode providing similar SFN performance as the data subframe can be of interest in 5G.

5.2.4 System-Level Simulations

Based on system level simulations results that are presented in Section 4.4.5, this subsection summarizes the main comparison between unicast and SC-PTM in the IMT-2020 test environments for eMBB dense urban and rural as detailed in [18] and where the specific parameters to the simulations are detailed in Annex A.3. The main KPIs used for comparison are the average and 5-%ile user spectral efficiencies.

From the studies, the following conclusions can be extracted:

- In **dense urban and rural IMT-2020 test environments** the user spectral efficiency of **cell-edge users** is higher for SC-PTM as compared to that of unicast transmission in all the considered cases.
- In **dense urban and rural IMT-2020 test environments unicast has shown to outperform SC-PTM in terms of average spectral efficiency when there is a low density of users** (approximately 15 users per cell) as it provides a better average user spectral efficiency with negligible packet loss rate due to the link adaptation and HARQ schemes. On the other hand, **SC-PTM outperforms unicast transmissions for higher density of users** as it provides higher average user spectral efficiency by using an MCS setting that provide an affordable packet loss rate of 10^{-3}.
- For **indoor hotspot scenario as defined in IMT-2020 test environment, unicast transmission mode has shown to be more promising than SC-PTM** because the packet loss rate with SC-PTM is beyond an affordable rate of 10^{-3} even at the lowest MCS setting, due to strong interferences which is contributed by the dense deployment of the indoor hotspot scenario. Hence, to use broadcast without violating the packet loss rate requirement, the interference level should be reduced by switching off some of the access points or by using SFN schemes.

5.3 WP2 Use-Case summary evaluation

This report has focused on the evaluations for the eMBB usage scenario of IMT-2020 evaluation process. Next a summary evaluation of the most representative use cases for this usage scenario is discussed.

5.3.1 Use Case M&E 1: Hybrid broadcast service

One instance of this use case embodies the delivery of a combination of UHDTV linear content (broadcast) and broadband access (unicast) to mobile handsets at national scale. The environment could target mainly outdoors but a Public Service Media (PSM) could also be interested that the broadcast signal covers fixed rooftop receivers. This would allow the PSM to use the same network to cover mobile handsets and fixed rooftop receivers (i.e. a converged network). In an outdoor environment, receivers can be either static or can be moving at high speeds (up to 250 km/h). Indoor coverage for both the broadcast and unicast signals is less important for this evaluation use case, since the Hybrid-Broadcast service in the home could be provided by a combination of fixed network plus the broadcast signal from the rooftop aerial. Since the coverage area needs to be at a national scale, the network should be able to cope with both dense urban environments and less densely populated rural areas equally.

The type of service described above requires a combination of PTP (to deliver unicast) and PTM transmissions (to deliver the broadcast). The research in this report has shown that, for the PTM component, ATSC 3.0 provides better performance than the PTM solutions in LTE for the channels and configurations studied. Although ATSC 3.0 also includes a return channel in its specifications, LTE has to date a predominant worldwide market position for the delivery of mobile broadband services to smartphones and tablets. It could therefore be beneficial to have a single chipset containing both PTP and PTM capabilities in the devices.

The delivery of broadcast by PTM transmission at national scale requires the network to be able to cover different environments, e.g. coverage to indoor, outdoor and vehicles. The results in section 4.4.4.1.7, which present a summary of the coverage in different environments, show that a network based solely on HPHT (with large inter-site distances of ca. 60 km) is unlikely to be able to cover all the required environments. Using an appropriate CP length, SNR values of around 15 dB can be achieved for fixed rooftop reception (assuming 95% location probability), the environment that this type of deployment has traditionally targeted. However, using the same network (with the same location probability target), if the goal is to deliver portable outdoor reception to handhelds, the available SNR can drop below 0 dB, which would not allow current transmission approaches to deliver useful bit-rates for the transmission of audio-visual services. The provision of services to handhelds in portable outdoor environments requires denser networks that are normally deployed in a LPLT topology. The results in section 4.4.4.1.7, show that LPLT network deployments with inter-site distance of 1.7 km can provide coverage with high SNR values (also assuming 95% location probability), e.g. more than 20 dB in portable outdoor environments, around 15 dB for handhelds in vehicles and more than 30 dB to vehicles with an external aerial. However, obtaining such a dense network in an entire country is not always practicable and rural areas typically experience considerably less dense networks. However, increasing the inter-site distance to 6 km as an example reduces, on average, the available SNR in all environments to 15 dB. As a practical example [39] shows that LPLT deployments in rural areas could exhibit even larger inter-site distances than 6 km. In these rural areas, HPHT networks could complement LPLT networks to increase the coverage and this possibility could be further explored in subsequent tasks of this project.

Finally, another important aspect is the transmission to receivers in mobile environments with speeds up to 250 km/h. As discussed in section 4.4.3.2, the recently standardised MBSFN mode with 200μs CP length (1.25 kHz inter-carrier distance) would not be able to meet the velocity requirements for 5G in large area networks with the high spectral efficiencies required to deliver UHDTV services.

5.3.2 Use Case M&E 2: Virtual/Augmented reality broadcast

The delivery of a fully immersive VR experience could encompass, for instance, the transmission of a live event (e.g. concert, sport event, etc.) over broadcast with unicast streams to adapt the content and allow interaction to each specific user.

As is the case for the hybrid broadcast service, this use case also requires a combination of PTP (to deliver unicast) and PTM transmissions (to deliver the broadcast).

This type of use case is characterised by extremely high data rates up to 5 Gbits/s. As presented in section 4.3.2, none of the technologies considered in this report is able to deliver such a bit data rate. To fulfil this the 5G-Xcast solution may therefore require the use of new frequency bands with wide bandwidth allocations and the use of MIMO techniques.

The environment in which this use case is delivered could be an indoor environment such as the eMBB Indoor Hotspot test environment from the IMT-2020 evaluation process and studied with system level simulations in 4.4.5. These evaluations showed that SC-PTM performs poorly in this instance due to strong interference which is the result of the dense deployments of the indoor hotspot scenario. In this case, the use of SFN schemes could significantly increase the available SNR and hence the service data-rate for the PTM component.

5.3.3 Use Case M&E 3: Remote live production

The remote live production use case has similar requirements to the previous use case in terms of the very high data rates required in the range of 100 Mbits/s (for mezzanine quality) to 9 Gbits/s (for uncompressed).

Although 100 Mbits/s can be achieved with today's PTM technology solutions, to achieve 9 Gbits/s would require the 5G-Xcast solution to explore the use of new frequency bands with wide bandwidth allocations and the use of MIMO.

This use case focuses primarily on the PTM transmission of the same video feed to the different potential users in the production environment. Hence, an integrated PTP (to deliver unicast) combined with PTM transmissions (to deliver the broadcast/multicast) is not critical to fulfil the requirements, although the presence of PTP could be useful for other production-related tasks.

The environment can be outdoors or indoors in a venue, however the users exhibit stationary mobility requirements. An eMBB Indoor Hotspot test environment (as defined in ITU-2020) and evaluated in 4.4.5 could be representative of this use case and here the system evaluations show that the use of SFN could reduce the interference levels currently experienced with SC-PTM.

5.3.4 Use Case PW: Multimedia public warning alert

Due to the importance for this type of use case to ensure that the users are able to receive the alerts, the coverage requirements are more stringent than for the previous use cases. In section 4.4.4.1.7 a representative 95% location probability has been used a representative value for mobile reception of M&E services. However, if the target is increased to 99% location probability this directly reduces the available SNR in the network. An important requirement for this use case is that the RAN should not cause receiver algorithms to dramatically decrease the battery life and that the frame structure so designed so as to allow a receiver to sleep efficiently. In this report energy efficiency has not been assessed but will be explored in subsequent tasks within this project.

5.4 Summary on potential limitations of LTE Broadcast RAN

Current LTE eMBMS RAN is configured with rigid OFDM numerology parameters that limit the type of network deployment. More specifically, eMBMS, including MBSFN and SC-PTM, is characterised by a limited set of waveform configurations, e.g., cyclic prefix length, in 3GPP Rel'14. The limitations on the waveform flexibility hinder LTE eMBMS in supporting the requirements of different network deployments as shown in Chapter 2, e.g., high coverage and high mobility in large area deployment for the hybrid broadcast service. Note that some of the requirements are challenging even for current PTP transmission technologies, e.g., the extremely high data rate and low end-to-end latency required in the virtual/augmented reality broadcast or in the remote live production scenarios. In addition, the lack of feedback channel in LTE eMBMS may disable the essential features of the network, e.g., supporting dynamic optimisation of resource allocation or providing useful audience metrics. Compared with ATSC 3.0, where spatial multiplexing techniques and high constellation sizes are available, the limitations in eMBMS Rel'14 results in an inability to support certain network deployments, e.g., large area deployment with a high spectral efficiency requirement.

The setup of an MBSFN area and related radio parameter configurations within the RAN is currently done statically, thereby limiting the dynamic provisioning of such services based on real-time traffic demands. The need for wide-area SFNs, especially for transmissions in frequency bands above 6 GHz, needs to be evaluated while designing the 5G-Xcast RAN. Currently, eMBMS requires separate user-plane infrastructure for connectivity of the RAN with the core network as well as for special MBSFN subframes over the air interface. While SC-PTM enables scheduling of data using PDSCH, the infrastructure requirements are similar to eMBMS. These aspects lead to a significantly large footprint in added infrastructure investments for the network operator as well as additional implementation complexity in the UE. Furthermore, this prompts the requirement of special middleware for reliable reception of such data.

One of the key design principles adopted for 5G RAN design would be to limit the added footprint for delivering PTM services over the existing PTP infrastructure and physical layer design. This would thereby limit investment costs and implementation complexity. Currently, the LTE eMBMS radio session setup procedure is complex and time-consuming; this requires simplification in 5G for enabling fast and efficient Xcast RAN sessions.

5.5 Proposals for MBMS Study Item in 3GPP

In the RAN plenary meeting #75, held in Dubrovnik (Croatia) in March 2017, three proposals were made to start a new Study Item on 5G broadcast in 3GPP Rel'15. Proposals came from three different proponents, as shown in Table 24. The first proposal (RP-170131) was supported by many members of this project (EBU, BBC, BT, IRT, Nomor and one2many). The three proposals were presented at the plenary meeting and it was observed by the chairman that they were very similar. The chairman asked the proponents to work together to create a joint proposal. The joint way forward proposal is shown in RP-170774. The document was supported by almost 20 companies. However, the chairman noted that, due to the lack of time units for Rel'15, the new study item could not be considered.

Some companies have continuously provided additional proposals in the following meetings. In the RAN plenary meetings #76 and #77, an additional proposal was made motivating the inclusion of MBMS as part of a non-standalone NR specification. Moreover, Qualcomm jointly with EBU and BBC also provided in RAN #77 a new Work Item (WI) description for a dedicated 5G MBMS service, and Samsung also contributed with an additional proposal for a SI on MBMS for NR. However, none of these proposals were progressed.

For the preparation of the work/study items to be included in Rel'16 the RAN chairman organised email discussions for different potential topics in order to scope the goals and the technical requirements of the candidate items. For Broadcast two separate items where identified: the first one on Terrestrial Broadcast (RP-180672) addressing downlink-only, large area coverage areas (up to nationwide) broadcast, and the second (RP-180669) on Mixed Mode Multicasting addressing downlink multicast/broadcast with the potential for it to be multiplexed and switched with unicast traffic with configurable coverage areas. While the terrestrial broadcast WID was targeting the LTE track, the mixed mode multicasting SID was targeting NR. At RAN#80 the different proposals were discussed and due to the limited resources on the number of time units against all the proposals on the table, especially for the NR track, the SID on mixed mode multicasting was not considered. However, the WID on Terrestrial Broadcast driven by Qualcomm together with members of the broadcast industry (EBU, BBC and IRT) was approved for inclusion as a SID on Rel'16 under the LTE track (RP-181342). This SID on 5G LTE Terrestrial Broadcast was widely supported by various member of the 5G-Xcast consortium (BT, Nomor, Nokia, One2many, Samsung and Expway) and this was crucial for the approval of the SID in 3GPP.

Table 24: List of relevant proposals presented in 3GPP on MBMS during Rel'15 and Rel'16.

RAN meeting	Company	Title	Document
#75	EBU	New SI: Study on MBMS for NR	RP-170131
	Samsung	New SID Proposal: Study on MBMS for NR	RP-170163
	Qualcomm	New SID: Study on MBMS in NR	RP-170448
#76	LG Electronics	Motivation for new WI on MBMS support for non-standalone NR	RP171046
#77	LG Electronics	New WID on MBMS support for non-standalone NR	RP-171629
	Qualcomm	WID on dedicated 5G MBMS for LTE	RP-172056
	Samsung	New SID Proposal: Study on MBMS for NR	RP-171807
#80	Qualcomm	WID on LTE-based 5G Terrestrial Broadcast	RP-180672
	Qualcomm	SID on NR mixed mode broadcast/multicast	RP-180669
	Qualcomm	Study on LTE-based 5G Terrestrial Broadcast	RP-181342

A Methodology and Parameters for Link Level, System Level and Coverage Simulations

A.1 Introduction to Methodology

The methodology for assessing the spectral efficiency performance of a system is split into two steps: the assessment of the CNR threshold, which is conducted via link level simulation and the estimation of the coverage area over synthetic and realistic scenarios by means of coverage and system level simulations, respectively.

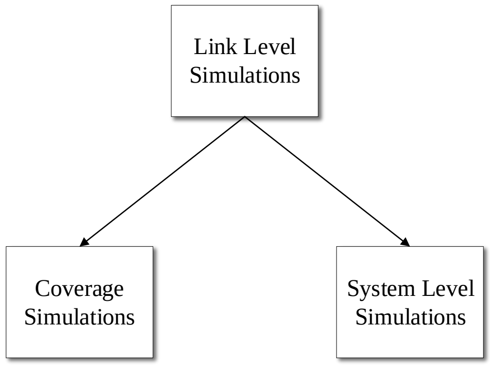

Figure 46: Performance simulation interconnection.

A.2 Link-Level Simulations

A.2.1 Methodology

This subsection focuses on the link-level simulations which take into account the possible configurations of a certain technology and how they are affected by scenario parameters.

Link level simulations can be structured in four main components, transmitter configuration, channel filtering, receiver configuration and error measurement. An overall link level simulator can be observed in Figure 47.

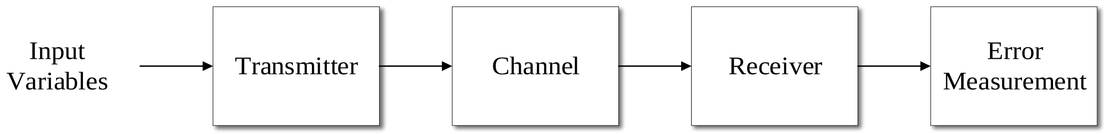

Figure 47: Generic link-level simulator block diagram.

Next sections provide a more in-depth explanation of each simulator block.

A.2.1.1 Transmitter

In the transmitter block, the input variables, i.e. the information bits from upper layers are channel encoded, mapped, interleaved, and OFDM modulated, according to the configuration under evaluation. Figure 48 illustrates the LTE transmitter block diagram.

A Transport Block (TB) is first segmented into several Coded Blocks (CBks), which are then encoded by a Forward Error Correction (FEC) procedure. The FEC is based on a concatenation of a Cyclic Redundancy Check (CRC) code and Turbo-Code (TC). Next, Rate Matching is performed, so that the bits of each CBk are interleaved, circular buffered and punctured. The CBks are then Scrambled and Mapped to a given QAM modulation (MAP). LTE Rel’14 provides 33 potential Modulation and Coding Scheme (MCS).

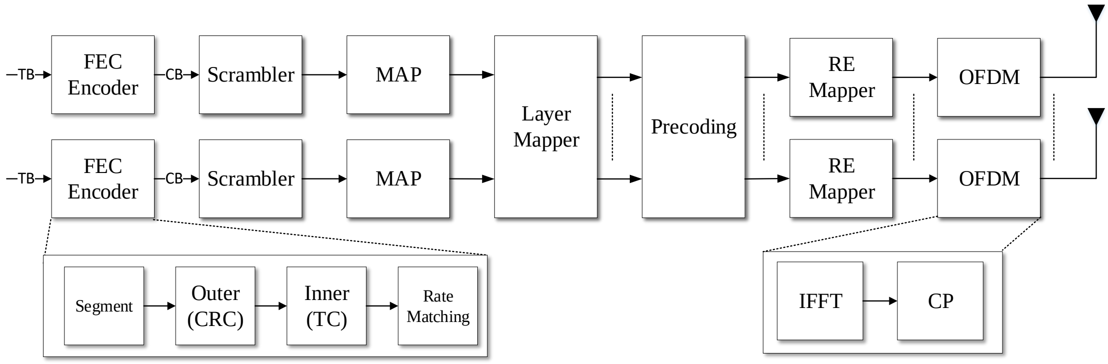

Figure 48: LTE Link-level transmitter block diagram.

The complex-valued modulation symbols are next mapped onto one or several transmission layers and precoded for transmission on the antenna ports. Resource Elements (RE) mapping is applied to the QAM symbols for each antenna port. Finally, the OFDM signal is generated by means of an inverse Fast Fourier Transform and the Cyclic Prefix insertion.

Figure 49 depicts the ATSC 3.0 transmitter block diagram. The ATSC 3.0 baseband signal is generated similarly as LTE. The input stream passes through a FEC encoder. However, the ATSC 3.0 FEC is based on a concatenation of the baseband packet payload (data bits), an outer Bose–Chaudhuri–Hocquenghem code (BCH) and an inner Low-Density Parity Check code (LDPC). The FEC frames are then Bit-Interleaved (BIL) and, if MIMO is applied, distributed to each antenna port by the Bit Demux. After dividing the data into two streams (in case MIMO is selected), bits are mapped to complex-valued non-uniform constellations (NUCs) forming FEC blocks. Overall, in contrast to LTE Rel'14, ATSC 3.0 allows up to 72 potential Modulation and Coding Schemes (ModCods).

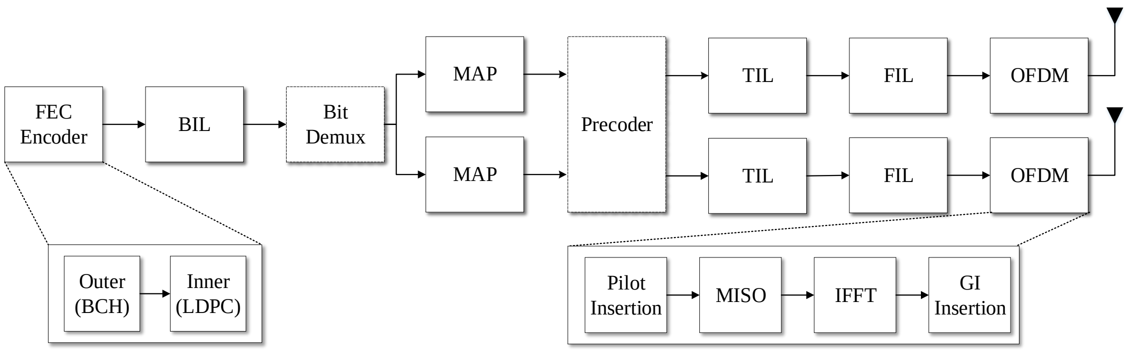

Figure 49: ATSC 3.0 Link-level transmitter block diagram

A MIMO precoding is applied to the mapped FEC blocks if it is desired. Next, the FEC blocks are Time (TIL) and Frequency (FIL) interleaved in order to provide time and frequency diversity, respectively. Last, the OFDM waveform is generated by inserting pilot carriers, filtering by a MISO pre-distortion scheme, and applying finally the inverse FFT and inserting the Guard Interval (GI).

A.2.1.2 Channel

The transmitted signal is then passed through a channel that models the time and frequency variations that the transmitted signal experiences through the channel. In multipath environments, the propagation delays are modelled by its Power Delay Profile (PDP). In mobile channels, the signal also fluctuates in time. At the receiver, the distorted signal has added noise according to the CNR under study. Different channel models have considered for this deliverable and which are described below.

A.2.1.2.1 AWGN Channel

The Additive White Gaussian Noise (AWGN) channel adds circularly symmetric complex Gaussian noise with variance σ^2 to the transmitted signal.

A.2.1.2.2 MIMO cross-polar i.i.d. Rayleigh Channel

A MIMO system with cross-polar antennas at both the transmitter and receiver with ideal cross-polarization factor (i.e. no coupling between polarizations) can be modelled using an independent identically distributed (i.i.d.) complex Gaussian random variables with zero-mean and varianceσ^2_{hij}. Each matrix component can be mathematically expressed as:

$$\mathrm{h_{i,j}} \sim \mathcal{CN}\left(0, \sigma^2_{h_{ij}}\right), \mathrm{i} = 1{,}2, \mathrm{j} = 1{,}2$$

where $\sigma^2_{h_{ij}}$ is the variance of the $i^{th}j^{th}$ path. In this report it is assumed that the cross-terms (i.e. h_{12} and h_{21}) are zero due to the ideal decoupling assumed, hence $\sigma^2_{h_{11}} = \sigma^2_{h_{22}} = 1$.

A.2.1.2.3 DVB-F1 Rice Channel

The DVB-F1 Ricean fading channel is used to describe the fixed rooftop-antenna reception conditions. The channel does not include any Doppler and should therefore be considered as a snapshot of the real time-variant channel. The model has 21-taps and it is modelled in [28].

A.2.1.2.4 DVB-NGH Portable Outdoor (NGH-PO) and DVB-NGH Portable Indoor (NGH-PI)

The DVB-NGH PO and DVB-NGH PI channels model reception conditions in portable (static) outdoor and indoor environments, respectively. They are constituted by 8 taps with different levels of Line-of-sight component. Detail information about the channel parameters can be found in [40].

A.2.1.2.5 Mobile TU-6 Channel

The profile in this channel models the terrestrial propagation in an urban area. It was defined by COST 207 as a typical urban (TU-6) profile and is made of 6 paths having wide dispersion in delay and relatively strong power. The profile parameters are given in [28].

A.2.1.3 Receiver

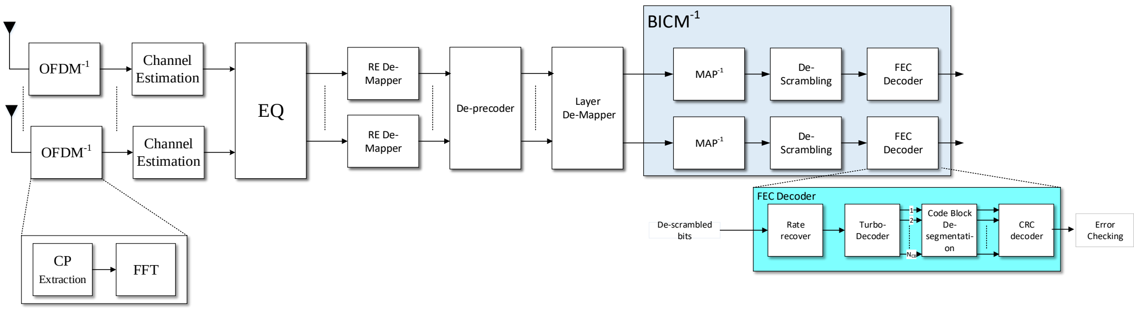

Figure 50: Generic receiver block diagram for SISO/MIMO (LTE).

For LTE, the receiver will first extract the CP (or GI) and transform the time signal to frequency domain by using FFT. Reference signals (or pilots), known by the receiver, are then used for estimating the noise power and the Channel Frequency Response (CFR). Mentioned that If MIMO is used, each receiver antenna will follow their own pilot pattern (according to antenna port number).

The estimated CFR is next used for equalization in order to obtain the transmitted complex-valued symbols. The de-mapping process converts the received complex-valued symbols into soft information which are then de-scrambled, followed by the FEC decoder part which including: rate recover, turbo decoder, Code Block De-segmentation, and CRC decoder. After all these processing, the transmitted bits are estimated.

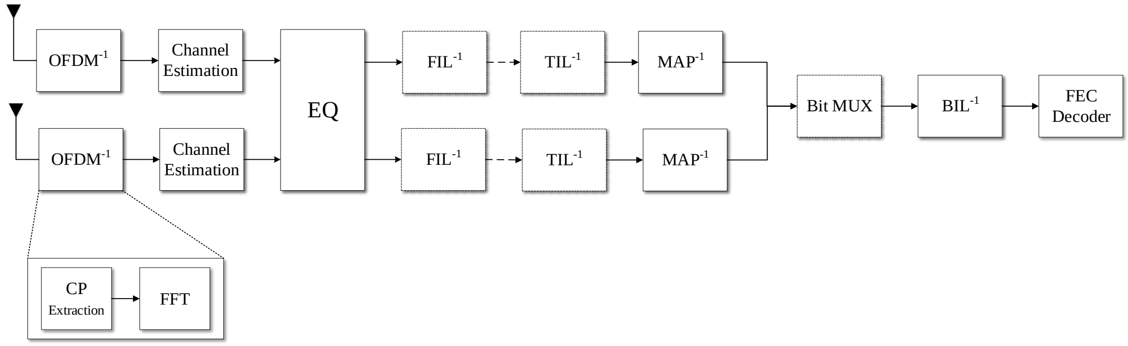

Figure 51: Generic receiver block diagram for SISO/MIMO (ATSC 3.0).

For ATSC 3.0, the receiver extracts the CP (or GI) and transforms the time signal to frequency domain by using an FFT. Reference signals (or pilots), known by the receiver, are then used for estimating the noise power and the CFR. The estimated CFR is next used for equalization in order to obtain the transmitted complex-valued symbols. They are then frequency and time de-interleaved, if any. The demapping process converts the received complex-valued symbols into soft information which are then de-scrambled (or bit deinterleaving). Finally, channel decoding is executed that computes estimates about the transmitted bits by the corresponding decoding algorithm.

A.2.1.4 Error Measurement

The error measurement is performed by comparing the decoded bits with transmitted bits in order to obtain Bit Error Rate (BER) and Block Error Rate (BLER) for a specific CNR. In particular, CNR thresholds for this deliverable are calculated for a BLER lower than 0.1% (10^{-3}) after outer decoder.

A.3 System-Level Simulations

A.3.1 Methodology

Link-level simulations are focused on a single link between a base station (be it a single base station of a MBSFN with multiple base stations) and a UE and analyse this with very high accuracy. This includes actual implementation of all layer-1 procedures like FEC encoding, modulation, distortion of the transmit signal by a fading-plus-noise channel and all the corresponding functions on the receiving side.

System-level simulations of communication networks, on the other hand, mimic considerably larger parts of a communication network consisting of multiple base stations and numerous UEs, gateways, application servers etc., i.e. including layer-2/3 and possibly higher. This allows for evaluation of aspects such as resource management, interference between different concurrent transmissions or higher-layer consideration, such as the impact of radio network performance on TCP connections or user experience at the application level. This may take into account UE distributions or mobility according to synthetic models or in “real-world” scenarios.

In order to obtaining meaningful simulation results for large systems, simulation accuracy must be sacrificed to some extent. A common approach that constitutes the next lower level of simulation accuracy compared to classical link-level simulations uses certain abstractions at layer-1. In particular, the complex operations of FEC en-/decoding, de-/modulation and convolution of the signal with a dispersive channel are typically omitted, but replaced with appropriate models. A typical chain of functions to emulate the physical layer processing, that is also used in system-level simulations in this project is illustrated in the Figure 52 below.

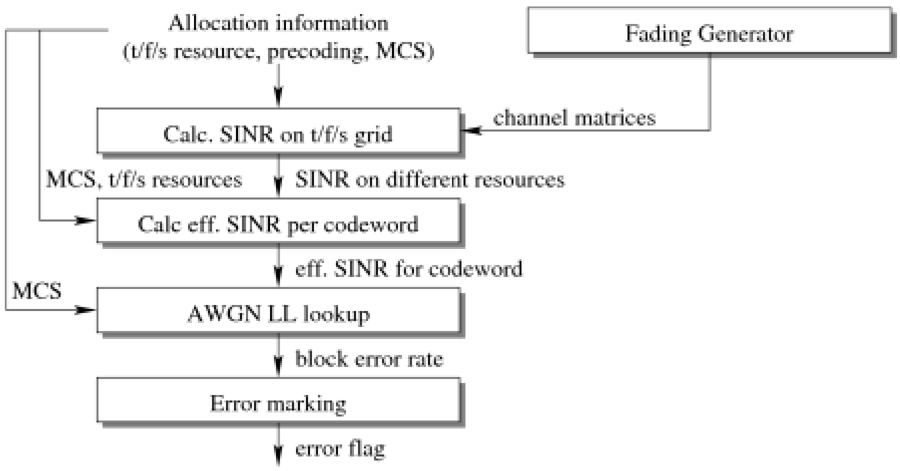

Figure 52: Emulation of Physical layer processing in System-Level Simulations

The individual steps are briefly described as follows:[3]

- The system-level simulator has—based on whatever criteria—allocated certain radio resources to a transmission, with a certain modulation and coding scheme (MCS) and a precoding scheme and passes them to the physical-layer emulator.
- A fading generator generates channel matrices in the equivalent complex baseband (ECB) for all relevant links (serving or interfering) based on positions, mobility, antenna parameters and many other parameters that affect the channel conditions.
- The first block “Calc. SINR on t/f/s grid” computes the effective SINR including MIMO precoding, OFDM modulation, fading channel, receiver filtering and potentially realistic channel estimation on the time / frequency / spatial resources used for a particular transmission. Thereby, the block channel modelling includes the addition of noise and interference arriving from other entities transmitting on the same radio resources. For a simple example of SINR computation for SU-MIMO without interference, cf. e.g. Eq. (6) in [51]; extending this to include other interference terms or applying arbitrary receive filters is rather trivial. To limit computational complexity, this is not done for every single resource element (QAM symbol) used in the transmission, but with reasonable sampling in time and frequency depending on the coherence time and bandwidth of the fading channels.
- The block “Calc. eff SINR per codeword” averages these SINR samples into a single effective SINR that is applicable to the whole codeword. “effective” here means that the expected error rate for this transmission given the current state of the transmission channel is (approximately) the same as that of a transmission of this codeword over a flat single-input-single-output (SISO) AWGN channel with

[3]As LTE is a MIMO-(DFTS-)OFDMA and NR is also expected to be based on the principles of MIMO-OFDM, let use this assumption for the sake of limited generalization in the description.

the eff. SINR as actual and constant SINR. For this, various approaches have been proposed in [52]. Of these models, the one called “Mutual Information effective SINR metric” (MIESM), cf. Eq. (1) with Eq. (4) of [52] for OFDM or [53] for DFTS-OFDM, is highly accurate for powerful coding schemes such as Turbo or LDPC codes. What it does, is that it computes from each eff. SINR sample obtained above how much mutual information can be transmitted per symbol assuming this SINR and modulation scheme. This is then aggregated over the different eff. SINR samples to derive the total amount of mutual information that can be transmitted within the codeword for the current channel state. Via the same relation between SINR and mutual information for a given modulation scheme the effective SINR over the entire transmission is obtained. This is highly accurate if it can be assumed that each data bit is uniformly represented by each of the code bits, which is reasonably true for powerful coding schemes such as Turbo or LDPC codes, but not so much e.g. for convolutional codes.

- The effective SINR for the codeword is then passed to the block “AGWN LL lookup”. This block holds lookup tables of BLER vs. SNR for each MCS. These may be obtained e.g. via link-level simulation for the AWGN channel with noise being applied directly on BPSK-modulated code bits. Hence, all this block does, is to report the BLER corresponding to the eff. SINR received from above from these tables using the MCS as an index.
- Finally, the block “Error marking” performs random error marking of the codeword with the probability reported by the above block. The thus marked codeword is then passed to the receiving protocol stack, where the physical layer only needs to check the error flag to determine how to further proceed with the packet, i.e. discard it and possibly ask for a retransmission, if it was received in error or pass it on to higher layers for further processing if received without error.

This procedure of layer-1 emulation can basically be applied to any transmission simulated in the system-level simulator, i.e. not only for data channels, but also for layer-1/2 control channels, where of course the accuracy of the MIESM averaging has to be checked on a case-by-case basis.

With this, large portions of communication networks can be simulated while the complexity of the simulation with link-level accuracy would be prohibitive. In order to avoid edge-effects a wraparound model is typically applied.

The value of this simulation approach is that one can simulate actual flows of data packets throughout the network as in a real system and hence implement and analyse various protocol layers and procedures, such as signalling or radio resource management.[4]

Results that are statistically relevant for a given scenario are obtained by performing simulations for numerous “drops” of UE positions and other parameters that are variable within the scenario, such as small-scale and large-scale parameters of the channel model.[5]

[4]Beyond this, there are more abstracted simulation approaches, where there is no transmission of individual packets with re marking, but a mere mapping of average SINR, computed in a simpler manner e.g. ignoring all effects of fast fading, and resource shares allocated to a particular traffic connection to a throughput for this connection. This typically facilitates even faster simulation and / or larger scenarios to analyse algorithms running on a much slower time scale, such as mobility robustness optimization, but at a further reduced accuracy, not allowing for analysis of protocol layers.

[5]We note that for coverage evaluation of pure broadcast modes that are not adaptive to the instantaneous UE distribution or their channel conditions, a simple scanning of the area with reference UE positions, i.e. in a deterministic manner, can be applied instead.

A.3.2 Test Environments and Simulation Parameters

Reference [23] defines 5 test environments for the evaluation of radio interface technologies for IMT-2020, i.e., indoor hotspot, dense Urban-eMBB, Rural-eMBB, Urban Macro – mMTC, and Urban Macro – URLLC. These test environments and parameters generally constitute the simulation assumptions for NR, in particular in terms of UE distributions, channel modelling and such. The system level simulations performed in this report for LTE Advanced Pro Broadcast use the test environments and parameters as defined in [23], but adaptations are made to reflect LTE constraints, e.g. in terms of antenna configurations, channel bandwidth and carrier frequency.

Table 25, Table 26, and Table 26 show the test environments used in this report, the selected configurations from [23] and the parameters.

Table 25: Evaluation parameters and configuration for Dense Urban-eMBB

Parameters	Dense Urban-eMBB
Configuration	A
Carrier frequency for evaluation	2 GHz
Total transmit power per TRxP	41 dBm for 10 MHz bandwidth
Number of antenna elements per TRxP	4
Inter-site distance	200 m
Percentage of high loss and low loss building type	20% high loss, 80% low loss
Number of UE antenna elements	4
Device deployment	100% indoor, and 100% outdoor (in car) uniformly distributed over the area under macro layer
UE mobility model	Fixed and identical speed |v| of all UEs of the same mobility class, randomly and uniformly drop. Speed is taken into account in the small scale channel.
UE speeds of interest	Indoor users: 3km/h Outdoor users (in-car): 30 km/h
BS noise figure	5 dB
UE noise figure	7 dB
BS antenna element gain	14 dBi
BS antenna elevation 3dB beamwidth	10°
BS antenna azimuth 3dB beamwidth	65°
UE antenna element gain	0 dBi
Thermal noise level	-174 dBm/Hz
Traffic mode	Full buffer
Simulation bandwidth	10 MHz+10 MHz for FDD
Link Level Channel model	3GPP TR 38.901
UE density	Various values evaluated with simulations
UE antenna height	1.5 m

Table 26: Evaluation parameters and configuration for Rural-eMBB

Parameters	Rural-eMBB
Configuration	B
Carrier frequency for evaluation	2 GHz
BS antenna height	35 m
Total transmit power per TRxP	46 dBm for 10 MHz bandwidth
Number of antenna elements per TRxP	4
Inter-site distance	1732 m

Percentage of high loss and low loss building type	100% low loss
Number of UE antenna elements	4
Device deployment	100% indoor, and 100% outdoor (in car) uniformly distributed over the area under macro layer
UE mobility model	Fixed and identical speed |v| of all UEs of the same mobility class, randomly and uniformly drop. Speed is taken into account in the small scale channel.
UE speeds of interest	Indoor users: 3km/h Outdoor users (in-car): 120 km/h
BS noise figure	5 dB
UE noise figure	7 dB
BS antenna element gain	14 dBi
BS antenna elevation 3dB beamwidth	10°
BS antenna azimuth 3dB beamwidth	65°
UE antenna element gain	0 dBi
Thermal noise level	-174 dBm/Hz
Traffic mode	Full buffer
Simulation bandwidth	10 MHz+10 MHz for FDD
Link Level Channel model	3GPP TR 38.901
UE density	Various values evaluated with simulations
UE antenna height	1.5 m

Table 27: Evaluation parameters and configuration for Indoor Hotspot-eMB

Parameters	***Indoor Hotspot-eMBB***
Configuration	A
Carrier frequency for evaluation	2 GHz
BS antenna height	3 m
Total transmit power per TRxP	24 dBm
Number of antenna elements per TRxP	4
Inter-site distance	20 m
Number of UE antenna elements	4
Office floor dimension	120 m x 50 m
BS antenna element gain	5 dBi
UE antenna element gain	0 dBi
Thermal noise level	-174 dBm/Hz
UE density	Various values evaluated with simulations
UE antenna height	1.5 m
Traffic mode	Full buffer
Simulation bandwidth	10 MHz+10 MHz for FDD
Link Level Channel model	3GPP TR 38.901
BS noise figure	3 dB
UE noise figure	7 dB

A.4 Methodology for Coverage Simulations

Coverage areas are determined based on synthetic hexagonal layouts and realistic scenarios.

A.4.1 Network Layout

The physical layout of the network including factors such as the transmitter locations, heights and powers are described. The topologies include low power low tower (LPLT) and high power high tower (HPHT) deployments.

Figure 53 sets out a network which contains 91 transmitters arranged in a regular hexagonal grid with five transmitter 'rings' of transmitters surrounding the one at the centre. Table 28 sets out the physical details for the considered networks.

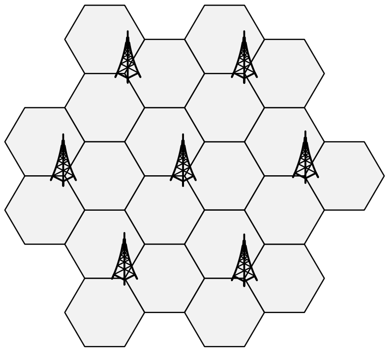

Figure 53: Regular hexagonal network configuration

Table 28: Physical parameters of coverage simulations (Bandwidth = 10 MHz)

Network Configuration	Comment	Effective height (m)	ERP (kW)	ISD (km)	HRP	VRP
HPHT1	Urban height loss (23.5dB EBU doc)	250	50	60	Omni	Omni
HPHT2	Urban height loss (23.5dB EBU doc)	350	50	80	Omni	Omni
LPLT1 (rural)	Rural Height loss Rural eMBB Configuration A	35	16dBW+8 dBi = 24dBW EiRP = **21.85dBW ERP** 10MHz BW	1.732	Omni	Omni
LPLT2 (rural)	Rural Height loss Rural eMBB Configuration C	35	16dBW+8 dBi = 24dBW EiRP = **21.85dBW ERP** 10MHz BW	6	Omni	Omni
LPLT3 (Urban)	Rural Height loss Urban Macro-mTC Configuration B	25	16dBW+8 dBi = 24dBW EiRP = **21.85dBW ERP** 10MHz BW	1.732	Omni	Omni

A.4.2 Receiving conditions

Table 29 sets out the parameters related to the receiving environment used in the simulations. The values are obtained from EBU Technical Report 034 "Simulation Parameters for Theoretical LTE eMBMS Network Studies.

Table 29: Reception conditions for hexagonal coverage simulations

Parameter	Fixed Roof-Top Reception	Portable Outdoor Reception	Portable Indoor Reception

Receiving Antenna Height (m)	10	1.5	1.5
Height Loss (dB)	0	23.5[6]	23.5[1]
Building Penetration Loss (dB)	0	0	11
Receiver Noise Figure (dB)	6	9	9
Rx Antenna Pattern	ITU-R BT.419	Omni-directional	Omni-directional
Rx Antenna Gain	13.15 dBi	-7.35 dBi	-7.35 dBi
Antenna Cable Loss (dB)	4	0	0
Implementation Margin (dB)	1	1	1
Body Loss (dB)	0	2	2
Noise Bandwidth (MHz)	4.5	4.5	4.5
Frequency (MHz)	700	700	700

A.4.3 Propagation Model

Table 30 sets out the parameters used for path loss and field strength estimation.

Table 30: Propagation model parameters for hexagonal coverage simulations

Propagation Model	ITU-R P.1546-5 over land
Wanted Signal Time Value	50% time
Interfering Signal Time Value	1% time
Location Variation	5.5dB (log-normal distribution)
Location Variation correlation	None
Signal Summation	Schwartz & Yeh power sum
Pixel size	100m x 100m

The mean signal strengths of the wanted and interfering signals in 100m x 100m 'pixels' are used to predict the probability of the signal being received at any point within the pixel. It is further assumed that the variation of all signals from one location to another within a pixel is log-normally distributed with a 5.5dB standard deviation. The Schwartz and Yeh method, or similar, is then used to combine the signals where appropriate. Additionally, the 50% time wanted and 1% time interfering signal levels are normally used in these calculations.

A.4.4 Single Frequency Network

In an SFN, the coverage is linked to the SINR which can be calculated as [45]:

$$SINR = \frac{\sum_i P_i \cdot Q(t_i - t_0)}{\sum_i P_i \cdot [1 - Q(t_i - t_0)] + P_{Ext} + P_N}$$

Where P_i and t_i are the received power and arrival time of the signal reaching the receiver from transmitter i, and t_0 is the initial time of the temporal synchronization. P_{Ext} is the received power of any external interference, and P_N is the thermal noise power.

Q is a weighting function applied to each contribution according to its arrival time to the receiver. The synchronization strategy followed by conventional OFDM receivers depends on its implementation as described in [43]. The weighting function Q is usually

[6] According to ITU-R BT.2254, table A1.5 suggests 16.5 dB for rural, 17 dB for suburban and 23.5 dB for dense urban scenarios.

modelled by means of a quadratic function, where T_U, T_{CP}, and T_{EI} are the useful symbol period, the CP duration and the equalization interval, respectively.

$$Q(t_i - t_0) = Q(\tau) = \begin{cases} 1, & 0 \leq \tau \leq T_{CP} \\ \left(1 - \frac{(\tau - T_{CP})}{T_U}\right)^2, & T_{CP} \leq \tau \leq T_{EI} \\ 0, & rest \end{cases}$$

The term $\sum_i P_i \cdot [1 - Q(t_i - t_0)]$ accounts for the received power of the interferences produced within the network.

The equalization interval directly depends on the selected pilot pattern as well as the channel estimation algorithm implemented at the receiver. State-of-the-art OFDM receivers generally apply frequency- and time- channel interpolations (referred to as 2D channel interpolation). The channel is first estimate in the frequency domain, by interpolation between pilot sub-carriers and, afterwards, between OFDM symbols. Assuming both time and frequency interpolation, T_{EI} can be aproximated by T_U/D_X, where D_X represents the frequency separation between pilot subcarriers.

State-of-the-art OFDM receivers generally apply frequency- and time- channel interpolations (referred to as 2D channel interpolation). The channel is first estimate in the frequency domain, by interpolation between pilot sub-carriers and, afterwards, between OFDM symbols.

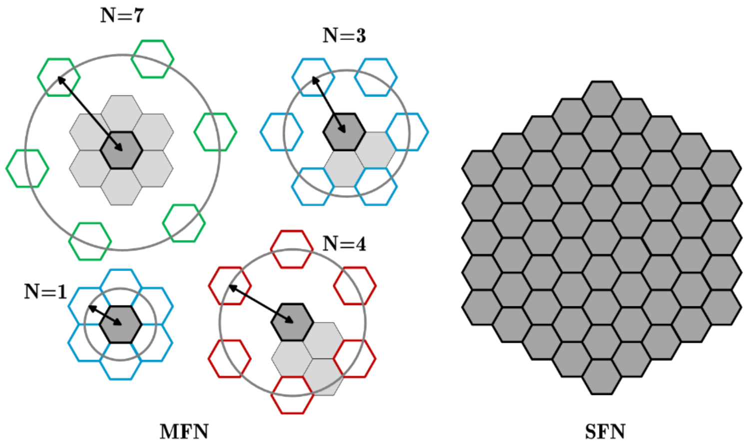

Figure 54: Hexagon-based topologies for generic coverage analysis using MFN (left) and SFN (right).

Figure 54 depicts the reference networks used to model an MFN and SFN for hexagon-based coverage simulations. For the MFN (left), frequency reuses 1,3,4 and 7 are used, what means that the same frequency is active only at certain transmitters along the network (represented as the coloured hexagons). The dark grey hexagons are the cells under study. Note that the frequency reuse 1 case effectively translates into all stations transmitting using the same frequency. In the SFN (right), all stations are active and considered to transmit the same content in a synchronized fashion.

Figure 55 presents a scheme of a network deployment consisting of the use of reserved cells tiers between different SFN areas and the use of frequency reuse between SFN clusters. Note that the clusters can be optimized in size so that they fit into the CP duration, thus limiting SFN self-interference.

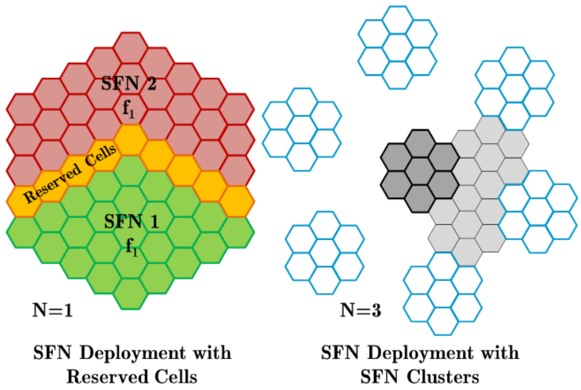

Figure 55: Network deployment consisting of the use of reserved cells tiers between different SFN areas and the use of frequency reuse between SFN clusters.

A.4.5 Coverage Criteria and Coverage Area

Coverage quality is to be expressed in percentage locations in a pixel. A pixel can be considered covered if the locational probability exceeds the appropriate threshold for 99% of the time. Common locational thresholds are: 70, 90, and 95% locations.

The coverage for a nationwide deployment is evaluated under the limits of the area defined by the 5 hexagon tiers as shown in Figure 55.

A.5 Link-level simulation results

A.5.1 eMBMS Link-Level Simulation Parameters

The air interface parameters of eMBMS, including MBSFN and SC-PTM, are presented in Table 31 and Table 32, with bandwidth of 5 MHz. Different MCS indexes are selected to provide the performance of the systems for different spectral efficiencies. For MBSFN and SC-PTM configurations, each MCS index employs a different modulation and TB size, which is directly related to a code-rate. MCS indexes follow the nomenclature used in [54]. The MCS index here is for the range 0 - 27 equal to the one defined by 3GPP [26] in Table 7.1.7.1-1. The higher indices 28 - 34 are for 256 QAM and correspond to indices 20 - 26 in Table 7.1.7.1-1A.

- MCS from 0 to 9: QPSK.
- MCS from 10 to 16: 16QAM.
- MCS from 17 to 27: 64QAM.
- MCS from 28 to 34: 256QAM.

An optimum ML demapper is employed in all cases (MMSE equalizer is considered for SC-PTM in case 2). Ideal channel estimation is considered during the simulation of all channels, while real channel estimation with linear interpolation in time and frequency domains is considered to evaluate the performance limits in mobile channels with practical estimation algorithms. Regarding the simulation length to obtain statistically reliable results, for each MCS index a maximum number of 10^5 subframes and a minimum number of 500 erroneous subframes are simulated for every CNR value.

The following tables show the parameters utilised with the MBSFN and SC-PTM specifications for the studies in this report.

Table 31: eMBMS Rel 14 Link-Level configurations

Parameter Name	Value
Bandwidth	5 MHz

Subcarrier Spacing	15 kHz	7.5 kHz	1.25 kHz
Number PRB	25		
Used subcarriers	300	600	3600
Number of Subcarriers (FFT size)	512	1024	4096
Number of subcarrier per RB	12	24	144
Cyclic Prefix	Extended		
T_u	66.67 µs	133.33 µs	800 µs
T_g	16.67 µs	33.33 µs	200 µs
$T_s = T_u + T_g$	83.33 µs	166.66 µs	1 ms
OFDM symbols per subcarrier	12	6	1
Modulation	QPSK, 16QAM, 64QAM, 256QAM		
Code Rate	Variable with MCS index		
Channel (de)coding	Turbo (de)/encoding with $R_c = \frac{1}{3}$, trellis=poly2trellis (4, [13 15],13)		

Table 32: SC-PTM Rel 14 Link-Level configuration

Parameter Name	Value
Bandwidth	5 MHz
Subcarrier Spacing	15 kHz
Number PRB	25
Used subcarriers	300
Number of Subcarriers (FFT size)	1024
Number of subcarrier per RB	12
Cyclic Prefix	Normal
T_u	66.67 µs
T_g	5.2 µs (first symbol) + 4.7 µs (rest)
$T_s = T_u + T_g$	71.87 µs (first symbol) + 71.37 µs (rest)
OFDM symbols per subcarrier	14
Modulation	QPSK, 16QAM, 64QAM, 256QAM
Code Rate	Variable with MCS index
Channel (de)coding	Turbo (de)/encoding with $R_c = \frac{1}{3}$, trellis=poly2trellis (4, [13 15],13)

A.5.2 ATSC 3.0 Link-Level Simulation Parameters

The air interface parameters of eMBMS, including MBSFN and SC-PTM, are presented for in Table 33. ATSC 3.0 implements a bandwidth of 6 MHz and includes in its specification a wide range of transmitter configurations including multiple FFT sizes, guard intervals, etc. In this deliverable, an FFT size of 8K with a GI of 1536 samples is selected to provide similar subcarrier spacing and duration of the cyclic prefix. Different modulation and coding combinations are selected to provide a representative set of spectral efficiencies. An optimum ML demapper is employed at the receiver. As with eMBMS, Ideal channel estimation is considered during the simulation of all channels, while real channel estimation with linear interpolation in time and frequency domains is considered to evaluate the performance limits in mobile channels with practical estimation algorithms.

The following table shows the parameters utilised with ASTC 3.0.

Table 33: ATSC 3.0 Link-Level configuration

Parameter Name	Value
Bandwidth	6 MHz
Subcarrier Spacing	843.75 Hz

FFT Size	8k
Number of used Subcarriers	6913
Length of GI	1024 samples
T_u	1185.185 µs
T_g	148.2 µs
$T_s = T_u + T_g$	1333.3 µs
Scattered Pilot pattern	SP.Dx = 6 SP.Dy = 2
Pilot Boosting	0[7]
Modulation	QPSK, 16NUC, 64NUC, 256NUC, 1kNUC, 4kNUC
Code Rate	{2-13}/15

[7] Pilots are only considered for the simulations on Section 4.3.3, where real channel estimation is used.

A.5.3 Minimum CNR required for a specific spectral efficiency

Table 34 shows the minimum CNR values obtained for MBSFN, for the evaluation criterion selected of a BLER < 0.1%. Six different channel models have been considered, and only representative MCS indexes have been selected for particular scenarios. Here, all the subframes are dedicated to PTM, i.e. no subframes are used for unicast and the non-mbsfn subframe region is of zero size.

Table 34: Minimum CNR (dB) required per MCS index for MBSFN (△f = 1.25 kHz)

MCS Index	BICM Spectral Efficiency (see note 1)	Spectral Efficiency (see note 2)	AWGN	i.i.d. Rayleigh	DVB-F1 Rice	Portable Outdoor	Portable Indoor	TU6 mobile (120km/h)
0	0.23	0.13	-5.2	-4.7	-4.5	-1.4	6.8	2.6
1	0.30	0.18	-4.1	-3.5	-3.4	-	-	-
2	0.37	0.21	-3.2	-2.4	-2.5	-	-	-
3	0.48	0.28	-2.1	-1.2	-1.4	2.0	10.2	6.2
4	0.60	0.35	-1.1	-0.1	-0.5	-	-	-
5	0.73	0.43	-0.2	1.1	0.5	-	-	-
6	0.86	0.51	0.7	2.4	1.4	5.1	13.9	9.9
7	1.03	0.61	2.0	4.3	2.5	-	-	-
8	1.16	0.68	2.7	5.5	3.4	-	-	-
9	1.33	0.78	3.8	7.2	4.5	10.3	18.3	14.2
10	1.33	0.78	4.1	5.7	4.7	-	-	-
11	1.46	0.86	4.7	6.4	5.2	-	-	-
12	1.65	0.97	5.6	7.5	6.0	9.8	18.9	14.6
13	1.91	1.12	6.6	8.8	7.1	-	-	-
14	2.16	1.26	7.7	10.1	8.3	-	-	-
15	2.35	1.41	8.5	11.2	9.4	19.8	24.6	19.8
16	2.54	1.51	9.1	12.2	10.1	-	-	-
17	2.54	1.51	10.0	12.1	10.7	-	-	-
18	2.74	1.56	10.6	12.8	11.1	19.7	25.4	20.8
19	3.06	1.78	11.6	14.0	12.3	-	-	-
20	3.31	1.93	12.5	15.1	13.1	-	-	-
21	3.56	2.08	13.3	16.1	14.0	23.8	29.0	24.6
22	3.82	2.23	14.2	17.1	14.8	-	-	-
23	4.24	2.45	15.5	18.9	16.2	-	-	-
24	4.56	2.64	16.3	20.2	17.0	31.1	35.0	29.9
25	4.72	2.75	16.9	21.1	17.7	-	-	-
26	5.10	2.98	18.0	23.4	19.1	-	-	-
27	5.28	3.09	18.8	25.1	19.9	37.9	40.9	35.2
28	5.28	3.09	19.5	22.5	20.3	-	-	-
29	5.48	3.20	20.0	23.1	20.7	-	-	-
30	5.86	3.43	21.1	24.5	21.9	35.2	38.9	33.8
31	6.12	3.58	21.7	25.4	22.5	-	-	-
32	6.54	3.87	22.8	27.5	24.2	-	-	-
33	6.76	4.02	23.5	28.6	25.1	42.9	45.4	39.9
34	7.06	4.17	24.6	30.8	26.0	-	-	-
	Note 1: BICM spectral efficiency (bpc) does not take into account loss due to guard interval, frequency guard bands, reference signals and CAS signalling, i.e. it does not include overheads. Note 2: Spectral efficiency (bits/s/Hz) does include loss due to guard interval, frequency guard bands, reference signals and CAS signalling, i.e. it does include overheads.							

Table 35 shows the minimum CNR values obtained for SC-PTM, for the same scenarios. Here, all the subframes are dedicated to PTM, i.e. no subframes are used for unicast and the non-mbsfn subframe region uses 3 OFDM symbols (CFI=3).

Table 35: Minimum CNR (dB) required per MCS index for SC-PTM

MCS Index	BICM Spectral Efficiency (see note 1)	Spectral Efficiency (see note 2)	AWGN	MIMO i.i.d. Rayleigh (see note 3)	DVB-F1 Rice	Portable Outdoor	Portable Indoor	TU6 mobile (120km/h)
0	0.22	0.13	-5.2	-2.1	-4.7	0.1	4.8	2.6
1	0.28	0.18	-4.0	-0.9	-3.5	-	-	-
2	0.34	0.21	-3.2	0.3	-2.6	-	-	-
3	0.45	0.28	-2.1	1.4	-1.5	3.4	8.8	5.9
4	0.56	0.35	-1.2	2.7	-0.6	-	-	-
5	0.68	0.43	-0.3	3.8	0.4	-	-	-
6	0.81	0.51	0.6	5.0	1.3	7.2	11.9	9.4
7	0.98	0.61	1.6	6.4	2.3	-	-	-
8	1.11	0.68	2.3	8.0	3.1	-	-	-
9	1.23	0.78	3.4	9.4	4.2	11.8	16.5	13.7
10	1.23	0.78	3.8	8.3	4.5	-	-	-
11	1.38	0.86	4.3	9.0	5.0	-	-	-
12	1.59	0.97	5.1	10.1	5.9	11.7	17.0	14.4
13	1.80	1.12	6.2	11.4	7.0	-	-	-
14	2.06	1.26	7.3	12.4	8.1	-	-	-
15	2.31	1.41	8.3	13.7	9.1	16.1	20.9	18.6
16	2.40	1.51	8.9	14.5	9.8	-	-	-
17	2.40	1.51	9.7	14.5	10.5	-	-	-
18	2.57	1.56	10.0	15.3	10.8	17.0	22.0	19.7
19	2.90	1.78	11.2	16.4	12.0	-	-	-
20	3.16	1.93	12.0	17.4	12.8	-	-	-
21	3.41	2.08	12.7	18.7	13.6	20.4	25.4	22.8
22	3.67	2.23	13.5	19.7	14.4	-	-	-
23	3.96	2.45	14.8	21.0	15.8	-	-	-
24	4.27	2.64	15.7	22.7	16.6	24.7	29.2	26.8
25	4.61	2.75	16.3	23.2	17.1	-	-	-
26	4.78	2.98	17.4	25.0	18.4	-	-	-
27	4.95	3.09	17.8	25.3	18.9	30.1	32.9	30.8
28	4.95	3.09	18.8	26.5	19.6	-	-	-
29	5.29	3.20	19.3	25.5	20.2	-	-	-
30	5.62	3.43	20.3	26.8	21.2	29.4	33.2	31.1
31	5.79	3.58	21.0	27.5	21.9	-	-	-
32	6.30	3.87	22.3	28.8	23.3	-	-	-
33	6.56	4.02	23.0	29.6	24.0	33.5	37.4	35.5
34	6.81	4.17	23.6	30.3	24.7	-	-	-

Note 1: BICM spectral efficiency (bpc) does not take into account loss due to guard interval, frequency guard bands, reference signals and CAS signalling, i.e. it does not include overheads.
Note 2: Spectral efficiency (bits/s/Hz) does include loss due to guard interval, frequency guard bands and reference signals, i.e. it does include overheads. The same overhead due to synchronisation is assumed as in MBSFN of 2.5%.
Note 3: Spectral efficiency on column 2 should be doubled for MIMO i.i.d. Rayleigh channel.

Table 36 shows the minimum CNR values obtained for ATSC 3.0. Note that for mobile channels, only CNRs for a time interleaving length of 200 ms are shown in this table.

Table 36: Minimum CNR (dB) required per ModCod index for ATSC 3.0

Mod.	Code	BICM Spectral Efficiency (see note 1)	Spectral efficiency (see note 2)	AWGN	MIMO i.i.d. Rayleigh (see note 3)	DVB-F1 Rice	Portable Outdoor	Portable Indoor	TU6 (120km/h) ΔT=200ms
QPSK	**2/15**	0.3	0.20	-6.2	-2.8	-6.1	-4.1	-1.8	-4.6
	3/15	0.4	0.31	-4.3	-0.7	-4.1	-	-	-
	4/15	0.5	0.41	-2.9	1.0	-2.6	-1.8	0.0	-0.8
	5/15	0.7	0.52	-1.7	2.5	-1.4	-	-	-
	6/15	0.8	0.62	-0.5	3.9	-0.2	0.7	2.7	2.2
	7/15	0.9	0.73	0.3	5.0	0.7	-	-	-
	8/15	1.1	0.83	1.2	6.2	1.6	2.9	5.0	4.5
	9/15	1.2	0.94	2.0	7.4	2.5	-	-	-
	10/15	1.3	1.04	2.8	8.7	3.4	5.1	7.6	7.0
	11/15	1.5	1.15	3.6	10.1	4.3	-	-	-
16QAM	**6/15**	1.6	1.25	4.2	9.1	4.7	4.6	7.9	7.2
	7/15	1.9	1.46	5.2	10.2	5.7	-	-	-
	8/15	2.1	1.67	6.3	11.7	6.9	7.6	10.5	9.9
	9/15	2.4	1.88	7.3	13.0	7.9	-	-	-
	10/15	2.7	2.08	8.4	14.4	9.0	10.8	13.4	12.6
	11/15	2.9	2.29	9.5	15.8	10.2	-	-	-
64QAM	**8/15**	3.2	2.50	10.3	15.8	10.9	11.8	14.6	13.9
	9/15	3.6	2.81	11.6	17.3	12.2	12.9	16.2	15.4
	10/15	4.0	3.13	12.9	18.9	13.5	15.2	17.7	17.0
	11/15	4.4	3.44	14.3	20.5	14.9	-	-	-
	12/15	4.8	3.75	15.6	22.4	16.3	-	-	-
256QAM	**10/15**	5.3	4.17	17.1	23.1	17.8	17.5	22.0	21.2
	11/15	5.9	4.59	18.8	25.0	19.5	19.2	23.9	23.1
	12/15	6.4	5.01	20.4	27.1	21.2	-	-	-
	13/15	6.9	5.43	22.2	29.6	23.1	-	-	-
1KQAM	**11/15**	7.3	5.73	23.4	29.8	24.2	-	-	-
	12/15	8.0	6.26	25.5	32.0	26.3	-	-	-
	13/15	8.7	6.78	27.6	34.7	28.4	-	-	-
4KQAM	**12/15**	9.6	7.51	30.3	37.0	31.2	-	-	-
	13/15	10.4	8.14	33.6	39.7	33.7	-	-	-
	Note 1: BICM spectral efficiency (bpc) does not take into account loss due to signalling, synchronization, sounding and Guard interval, i.e. it does not include overheads. Note 2: Spectral efficiency (bits/s/Hz) does take into account loss due to signalling, synchronization, sounding and Guard interval, i.e. it does include overheads according to the configuration of Table 33. Note 3: Spectral efficiency on column 2 should be doubled for MIMO i.i.d. Rayleigh channel.								

A.6 Coverage simulation results

Table 37, Table 38 and Table 39 show the available SNR in dBs for LPLT and HPHT networks in different environments of interest.

Table 37: Available SNR in dBs for LPLT networks in portable outdoor and portable indoor environments

CP and location %		Portable Outdoor Handheld				Portable Indoor Handheld			
		ISD= 6km BW=5 MHz	ISD= 6km BW=1.5 MHz	ISD= 1.7km BW=5 MHz	ISD= 1.7km BW=1.5 MHz	ISD= 6km BW=5 MHz	ISD= 6km BW=1.5 MHz	ISD= 1.7km BW=5 MHz	ISD= 1.7km BW=1.5 MHz
33 µs	70	11.4	15.2	26.7	31.0	0.0	5.5	15.3	21.1
	90	8.0	11.9	23.8	27.7	-5.5	-0.1	10.0	15.6
	95	6.3	10.2	22.0	26.2	-8.2	-2.8	7.5	13.0
	99	3.1	7.0	19.1	23.3	-13.3	-8.0	2.7	8.2
100 µs	70	12.2	18.1	27.4	33.4	0.14	6.1	15.5	21.8
	90	8.8	14.7	24.3	30.3	-5.4	0.6	10.2	16.2
	95	7.1	13.0	22.8	28.8	-8.15	-2.1	7.6	13.6
	99	4.0	9.8	20.0	26.0	-13.3	-7.3	3.0	8.7
200 µs	70	12.2	18.2	27.4	33.4	0.1	6.1	15.5	21.8
	90	8.8	14.8	24.3	30.3	-5.4	0.6	10.2	16.2
	95	7.1	13.1	22.8	28.8	-8.1	-2.1	7.6	13.6
	99	4.0	10.0	20.0	26.0	-13.3	-7.3	3.0	8.7
300 µs	70	12.2	18.2	27.4	33.4	0.1	6.1	15.5	21.8
	90	8.8	14.8	24.3	30.3	-5.4	0.6	10.2	16.2
	95	7.1	13.2	22.8	28.8	-8.1	-2.1	7.6	13.6
	99	4.0	10.0	20.0	26.0	-13.3	-7.3	3.0	8.7
400 µs	70	12.2	18.2	27.4	33.4	0.1	6.1	15.5	21.8
	90	8.8	14.8	24.3	30.3	-5.4	0.6	10.2	16.2
	95	7.1	13.2	22.8	28.8	-8.1	-2.1	7.6	13.6
	99	4.0	10.0	20.0	26.0	-13.3	-7.3	3.0	8.7

Note 1: The results for portable handheld outdoor/indoor include a receiver antenna efficiency of -7.35 dBi (see Annex A.4) and extracted from [54]. At the time of writing this report discussions and research if being carried out to confirm whether this value accurately represents this parameter or whether receiver antenna efficiencies closer to 0 dBi should be use.

Table 38: Available SNR in dBs for LPLT networks in vehicular environments

		Vehicular Internal Handheld				Vehicular External Aerial			
		ISD= 6km BW=5 MHz	ISD= 6km BW=1.5 MHz	ISD= 1.7km BW=5 MHz	ISD= 1.7km BW=1.5 MHz	ISD= 6km BW=5 MHz	ISD= 6km BW=1.5 MHz	ISD= 1.7km BW=5 MHz	ISD= 1.7km BW=1.5 MHz
33 µs	70	5.9	11.3	21.1	26.5	16.4	17.4	32.6	34.1
	90	2.2	7.5	17.7	23.1	13.0	13.9	29.3	30.7
	95	0.4	5.7	16.1	21.4	11.3	12.2	27.7	29.0
	99	-3.0	2.2	13.0	18.3	8.0	8.8	24.6	26.0
100 µs	70	6.1	12.1	21.3	27.3	21.3	26.6	36.8	42.8
	90	2.4	8.4	18.0	24.0	18.0	23.2	33.7	39.7
	95	0.6	6.6	16.3	22.3	16.3	21.5	32.2	38.2
	99	-2.8	3.2	13.2	19.2	13.1	18.3	29.3	35.3
200 µs	70	6.1	12.1	21.3	27.3	21.6	27.6	36.8	42.8
	90	2.4	8.4	18.0	24.0	18.2	24.2	33.7	39.7
	95	0.6	6.6	16.3	22.3	16.5	22.5	32.2	38.2
	99	-2.8	3.2	13.2	19.2	13.3	19.3	29.3	35.3
300 µs	70	6.1	12.1	21.3	27.3	21.6	27.6	36.8	42.8
	90	2.4	8.4	18.0	24.0	18.2	24.2	33.7	39.7
	95	0.6	6.6	16.3	22.3	16.5	22.5	32.2	38.2
	99	-2.8	3.2	13.2	19.2	13.3	19.3	29.3	35.3
400 µs	70	6.1	12.1	21.3	27.3	21.6	27.6	36.8	42.8
	90	2.4	8.4	18.0	24.0	18.2	24.2	33.7	39.7
	95	0.6	6.6	16.3	22.3	16.5	22.5	32.2	38.2
	99	-2.8	3.2	13.2	19.2	13.3	19.3	29.3	35.3

Note 1: The results for vehicular internal handheld include a receiver antenna efficiency of -7.35 dBi (see Annex A.4) and extracted from [54]. At the time of writing this report discussions and research if being carried out to confirm whether this value accurately represents this parameter or whether receiver antenna efficiencies closer to 0 dBi should be use.
Note 2: Vehicular external aerial includes a receiver antenna efficiency of 0 dBi.

Table 39: Available SNR in dBs for HPHT networks in fixed rooftop and portable outdoor environments (ISD=60 km)

		Fixed rooftop		Portable Outdoor Handheld	
		BW=5 MHz	BW=1.5 MHz	BW=5 MHz	BW=1.5 MHz
33 µs	70	10.3	10.3		
	90	5.4	5.4		
	95	3.1	3.1		
	99	-1.2	-1.2		
100 µs	70	12.2	12.2		
	90	7.1	7.1		
	95	4.6	4.6		
	99	-0.0	-0.0		
200 µs	70	19.2	19.2	3.3	
	90	14.6	14.6	0.1	
	95	12.3	12.3	-1.6	
	99	8.2	8.2	-5.0	
300 µs	70	22.7	22.8	3.4	
	90	17.9	17.9	0.1	
	95	15.6	15.6	-1.6	
	99	11.2	11.2	-4.9	
400 µs	70	26.8	26.9	3.4	
	90	22.1	22.2	0.1	
	95	19.8	19.9	-1.6	
	99	15.5	15.6	-4.9	
Note 1: The results for portable handheld outdoor include a receiver antenna efficiency of -7.35 dBi (see Annex A.4) and extracted from [54]. At the time of writing this report discussions and research if being carried out to confirm whether this value accurately represents this parameter or whether receiver antenna efficiencies closer to 0 dBi should be use.					

B Quality Assessment of LTE eMBMS in the laboratory

B.1 Introduction

This annex shows the results and methodology of the laboratory tests carried by IRT and BBC in two independent facilities on the performance of LTE eMBMS in AWGN channels for the delivery of video services.

In the laboratory tests the performance is evaluated from the video quality perspective. Hence, relevant metrics used in terrestrial broadcasting standards are presented and adapted for the evaluation of eMBMS. Since most of the evaluations of eMBMS by simulation are reported in terms of BLER at the physical layer (or at higher layers if Application Layer FEC are used), this annex also studies how the performance metrics to assess the video quality and the BLER can be linked. A methodology to measure the received SNR is also presented and discussed. Finally, this annex outlines the main conclusions derived from the measurements and outlines future lines of further research.

B.2 ESR5 Measurements over RTP-eMBMS

Traditionally the conventional BER has been used to simply characterize the physical layer performance, however more elaborated performance parameters, such errored-second-ratio (ESR), have been discussed in the past to assess the video broadcasting service reception. The reason behind relies on the fact that classical BER first order statistics are not sufficient for properly assessing video broadcasting quality reception.

If we focus first on DVB standards, the so called frame error ratio (FER), gets defined in the case of DVB-H/SH by the ratio between the number of application data tables (ADTs) containing errors and the total number of frames measured without any kind of link layer correction (MPE-FEC) included [105], [106]. Similar definition applies for DVB-T2, where FER is again the ratio between the number of the so called BBFRAME (base band frame) after the T2 base band scrambling containing errors, against the total number of T2 base band frames measured during a given observation period [106].

A similar metric gets derived for eMBMS, where BLER (block error rate) provides the ratio between the number of transport blocks containing errors and the total number of transport blocks measured, where the transport block is data packet that is delivered to the LTE MAC layer [107], [108].

Nevertheless, and even if FER is in general a representative indicator for the quality of reception of one service for terrestrial mobile broadcasting applications, the assessment of reliable video content reception based only FER/BER, is on the other hand insufficient when the observation time is long [109], [110]. This remark particularly applies in specific channel conditions and gets usually influenced in terms of performance depending on specific settings of the PHY layer. That could be for instance the case of the time interleaver stages implemented in the specific standard under analysis or if the system under study employs upper layer FEC correction mechanisms [110].

B.2.1 Key Performance Indicator in TV-Mobile Broadcasting Systems

In traditional DTT, broadcasters pay special criterion to the required SNR values for a reasonable quality reception. Measuring the bit error rate of a transmission while delivering a video is only suitable for fixed reception using rooftop antennas. According to [109], [110], [111] the 5% errored-second-ratio in 20s or ESR5-20 is an appropriate physical layer metric for reception quality.

The ESR5-20 criterion is achieved when in a time interval of 20 seconds there is at most one second in error. The ESR5-20 ratio is the ratio of windows for which ESR5 is fulfilled, over the total number of observation windows; it can be evaluated as [110]:

$$ESR5\_20 = 1 - \frac{\sum_{w=1}^{N_w} ceil\{\frac{\max[0; N_w^{sec}(w) - 1]}{20}\}}{N_w}$$

where N_w represents the number of observed window and $N_w^{sec}(w)$ represents the number of erroneous seconds inside a window. In case of the TU6 terrestrial channel, a ESR5_20 with a confidence of 99% is roughly equivalent to an FER = 1% for DVB-SH [110]. However, this assumption for the FER only applies for the mentioned TU6 channel and for DVB-SH system. In this sense, the same analysis also reflects that these criteria for the FER cannot be in general extrapolated to other channel scenarios. Therefore, the same conclusion can be applied when the assessment is provided for different terrestrial broadcasting systems.

B.2.2 IRT Measurement Setup for eMBMS

Figure 56 shows the setup of the measurement enabled at IRT. It consists of a LTE/eMBMS generator, noise generator, spectrum analyser, LTE/eMBMS measurement receiver (TSMW with Romes) and an eMBMS UE.

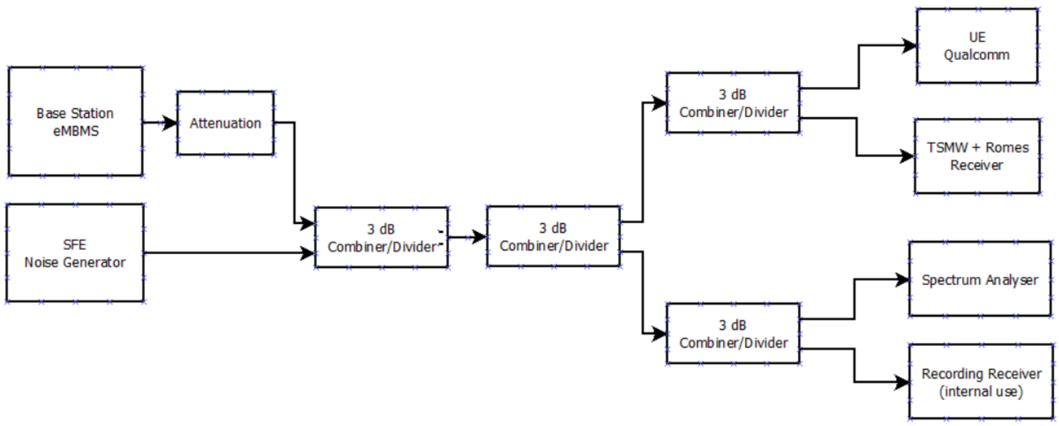

Figure 56: IRT Munich eMBMS laboratory setup

The eMBMS signal providing the RTP stream session under analysis is generated and transmitted by the Base Station provided by Nokia. Because of the high-level output, it is necessary to use attenuators. It also should be considered that the Base Station is not a typical measuring instrument for lab tests. That means that the output power is changing dynamically and therefore leads to a small fluctuation in the measured parameters. The SFE is used as a pure noise generator and will be added to the eMBMS signal via a 3 dB combiner. It must be noted that the original setup from Figure 56 includes only AWGN channel emulation but this setup will be further evolve to support also RF fading conditions.

After this the signal is fed to the spectrum analyser, to the Measurement Receiver and the UE to watch the Video. The Spectrum Analyser was used to see monitor the Spectrum, while the receiver was used to measure the SNR directly. To be able to apply the ESR5 criterion, the video was played at the UE.

B.2.3 Measurement Results under ESR5-20

At this point for different MCS configurations have been measured. In Table 40 the results show that there is a difference of about 4 dB. The simulated Values belong to the EBU TR 034 [54] for a BLER 1%. Although the ESR5 criterion may be subjective, the boundary of the SNR values would change rapidly. Even with a very conservative assumption the measurement error would be 0.2 or 0.3 dB because of the characteristic of a digital system.

Table 40: IRT Preliminary RTP-eMBMS measurements in AWGN channel

Spectral efficiency (b/s/Hz)	MCS Index	Modulation	EBU TR034 simulated (dB)	RTP and ESR5-20 measured (dB)
0,80	9	QPSK	3,9	8,5
0,99	12	16-QAM	5,6	10,1
1,41	15	16-QAM	8,5	12,5
1,64	18	64-QAM	10,7	13,8

The difference of the simulated and measured results may be related to the different criterions, the BLER and ESR5. The simulation assumes a BLER of about 1% and the measurement has been done with the ESR5 criterion. Using the ESR5 criterion is not sufficient to guarantee a good video quality in an AWGN channel but with an additional correction factor of a few tenths of dB it should be enough.

B.3 Block Error Rate Measurements over MPEG-DASH-eMBMS

After the laboratory tests performed by the IRT, the BBC R&D performed independent laboratory tests on the performance of eMBMS in AWGN channels. In the tests carried out by the BBC R&D the main goal was to try to verify the performance of eMBMS reported by simulation in terms of BLER in reference [54] . The next sections present the BBC laboratory set-up to carry the tests, the methodology to measure the received SNR at the receiver terminals, the mapping between MPEG-DASH segment error rate and BLER, the results obtained and finally derives some conclusions and further lines of research.

B.3.1 BBC Measurement Setup for eMBMS

Figure 57 shows the eMBMS laboratory set-up at BBC R&D used to perform the measurements.

Information of the components of the laboratory set-up is detailed in Table 41. In contrast to the IRT laboratory set-up, the LTE base station provides output powers in the order of -10 dBm. The power of the output signal and the noise generators are controlled by variable attenuators. The combined signal is injected to a screened box where the handsets are placed. Through a power splitter the same noisy eMBMS signal is injected to the spectrum analyser. A reference UE is used to verify that the output of the base station (without external noise sources) is transmitted and decoded successfully.

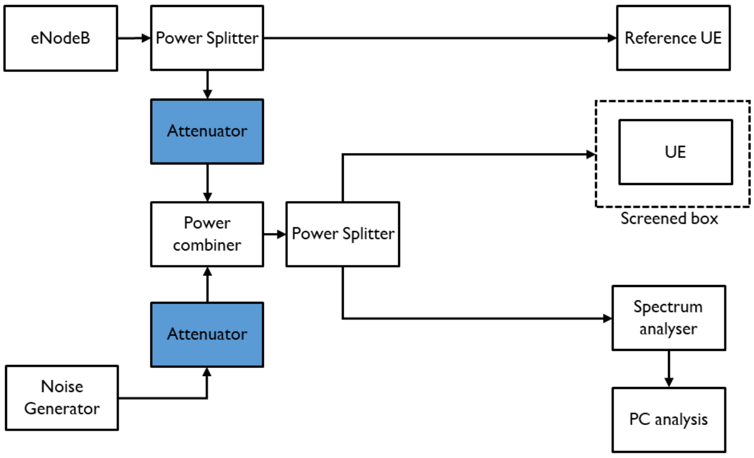

Figure 57: BBC R&D eMBMS laboratory setup

Table 41: BBC laboratory set-up components

Transmitter	BM-SC and eNB Rel'11/12
Channel	External AWGN source - Noise Com Inc. NC1109A
Receivers	Off-the-self tablets with eMBMS middleware incorporated and operating at Band 28 (769.5 MHz)
Spectrum Analyser	R&S FSV with EUTRA/LTE Analysis SW with eMBMS demodulation (although not required for the performance measurements.)

The signal at the spectrum analyser can be decoded by the R&S FSV with EUTRA/LTE Analysis SW with eMBMS demodulation. An example screenshot is shown in Figure 58. With this software, it can be easily verified that the transmitted signal is a useful eMBMS service where some basic characteristics of the signal can be quickly seen (e.g., spectrum shape, OFDM grid allocation, constellation size and some power measurements amongst others). However, this software is not used for the measurement of the SNR in the received eMBMS noisy signal as explained in the next section.

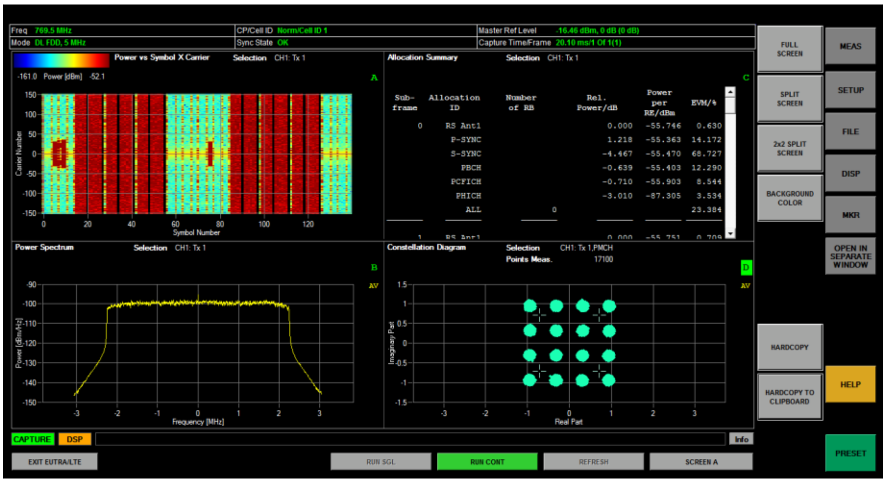

Figure 58: Decoded signal with R&S FSV with EUTRA/LTE Analysis SW

B.3.2 eMBMS SNR measurement procedure

The aim is to obtain an SNR measurement procedure that does not rely on specific LTE demodulation SW. To measure the signal power of the MBSFN frames, the Spectrum

Analyser is configured in zero span mode with the parameters shown in Figure 59. Here, the MBSFN frames can be easily differentiated since there is no unicast information transmitted, hence in those frames where unicast is scheduled there is almost no transmitted power.

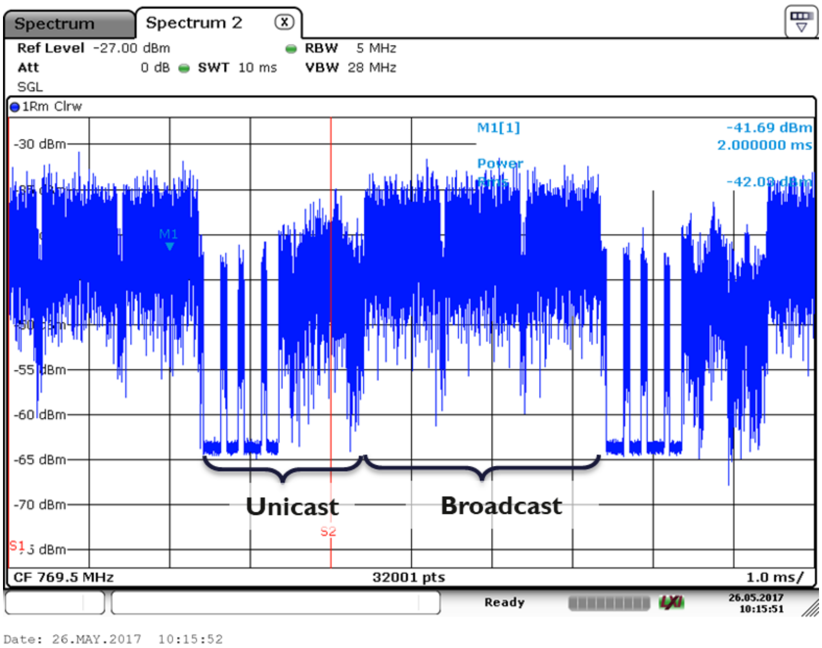

Figure 59: eMBMS SNR measurement procedure – time analysis

To obtain a reference SNR value that can be later used to measure when the errors occur at different noise levels the following steps are done (and illustrated in

Figure 60):

1. Measure signal power at MBSFN frames at zero span mode (time domain) without AWGN noise;
2. Measure noise power in data carriers (e.g., 4.515 MHz for 25 RBs) without eMBMS signal in frequency domain; and
3. Adjust signal and noise power to obtain the same level, i.e., SNR=0 dB.

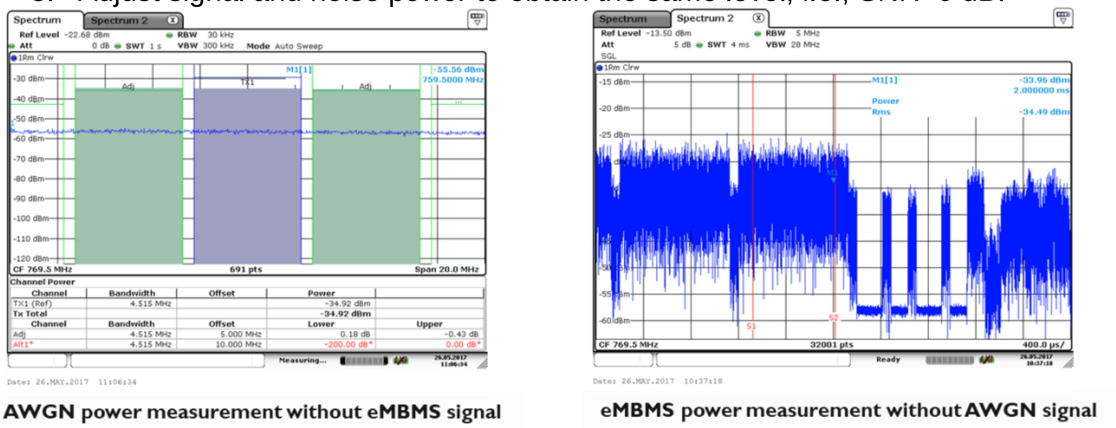

Figure 60: eMBMS SNR measurement procedure – Power measurements of MBSFN and Noise.

Step 1 is done in zero spam mode because measuring the total power in frequency domain in the useful band (i.e., 4.515 MHz in this case) would not provide an accurate measure of the power in the MBSFN frames. In the current configuration, both unicast and MBSFN frames are multiplexed where the unicast signals are in idle mode (in particular 6 subframes are allocated to MBSFN and 4 subframes for unicast). Hence, a power measure in the useful bandwidth takes into account both signals. Measuring the eMBMS signal in time domain allows to easily differentiate between unicast and MBSFN frames. For step 2, the noise can be measured in frequency domain in the useful bandwidth (i.e., 4.515 MHz in this case). Using this approach, we can ensure that the noise level at the MBSFN frames is configured accurately.

B.3.3 Mapping BLER at LTE PHY to MPEG-DASH segment Error Rate

In these experiments, Live MPEG-DASH video streams are used for evaluation of the eMBMS performance.

The experiment starts at high SNR values where the video stream is perfectly decoded and reproduced at the handsets. Then the noise level is increased (at 1 dB steps) until the video stream completely stops working. At this operating point, all the MPEG-DASH segments are in error, i.e., 100% MPEG-DASH segments error rate.

The aim of the experiments is to try to validate the simulated performance results of eMBMS reported in EBU TR034 at 1% BLER. However, MPEG-DASH Error rate and BLER are not directly comparable, since overheads of the different protocol layers need to be taken into account.

The overheads introduced at the different LTE protocol layers can be modelled as presented in Figure 61.

- MPEG-DASH video streams pass through layers of LTE protocol stack adding respective overheads.
- The Packet Unit Data (PDU) at the PHY layer, i.e., Transport Blocks (TB), include data plus x% of overhead

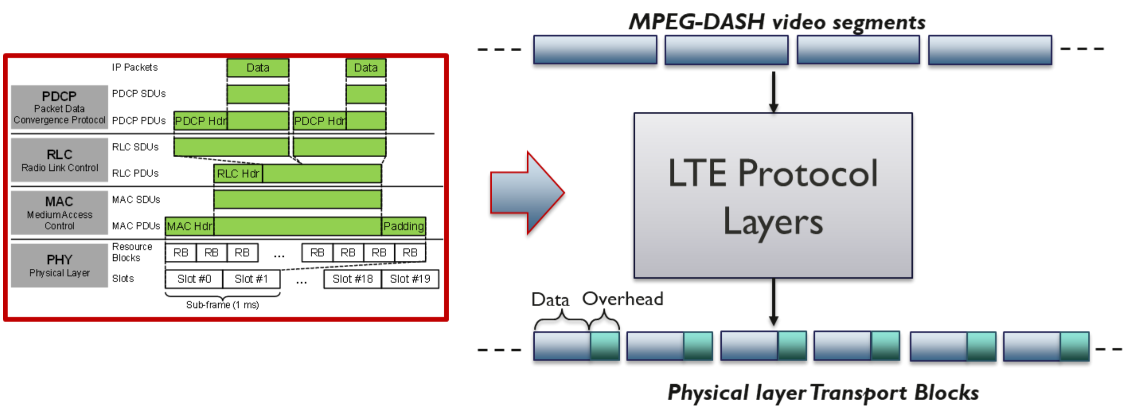

Figure 61: eMBMS simplified overhead analysis

The next step is to calculate to what MPEG-DASH error rate translates a BLER 1%. This calculation directly depends on the number of the number of Transport Blocks that form one MPEG-DASH segment. However, depending on the overhead that is introduced across the layers, the number of Transport Blocks that form one MPEG-DASH segment will vary. In these evaluations, the overhead value will be a parameter that will need to be verified.

For the AWGN channel it can be assumed that the errors will be uniformly distributed. In the case that one Transport Block at the physical layer is corrupted due to noise disturbance, the entire MPEG-DASH segment will be discarded. This concept is illustrated in Figure 62.

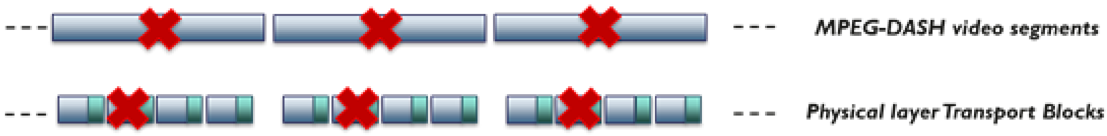

Figure 62: eMBMS simplified error rate analysis

In the figure, as an example, one MPEG-DASH segment is carried over 4 TB. A single error in any of the 4 TB will erase the entire MPEG-DASH segment. The Minimum Block Error Rate (BLER) at PHY layer to produce 100% MPEG-DASH Error Rate (MDER) for different number of TB in one MPEG-DASH segment can be approximated as:

$$BLER \approx MDER / N$$

where N is the number of TB in one MPEG-DASH segment. This does not take into account situation where one TB carries data from two MPEG-DASG segments, hence this approximation will provide optimistic results.

B.3.3.1 The Live video streams

The eMBMS specification allows for a wide set of modulation and coding schemes (MCS). To test different MCS available in the specification, three live video streams with different data rates were used in the experiments.

Table 42 shows the data rates and MPEG-DASH segment sizes and durations used in the tests.

Table 42: MPEG-DASH video streams parameters used in the experiments

Video Stream	Data rate* [kbps]	Segment duration [s]	Segment size [bytes]		
			minimum	**mean**	**max**
A	452	3.84	74474	153056	244150
B	715	3.84	91222	210139	399294
C	1427	3.84	263206	567889	734169

As it can be seen in Table 42, since the duration is kept constant, the size of the segments varies with the data rate stream. Also, the size in bytes of the segments in each stream is not constant. At Table 42 the minimum, mean and maximum sizes of the three video streams are detailed.

Table 43 presents for a 5 MHz bandwidth, for three MCS (5, 11 and 18) and for different overhead assumptions, the minimum BLER that needs to occur at the physical layer so all the MPEG-DASH segments are in error. (The higher the segment size, the more TB that fit in one segment, hence, the errors need to occur less often at the physical layer.) If an overhead of 33% is assumed with mean segment sizes it can be seen in the table that the minimum BLER at the physical layer to have 100% MDER is around 0.1%. Higher BLER would increase the number of TB in error although the MDER would have already achieved its saturating point. It is worth pointing out that these approximations are valid for an AWGN channel where the errors are evenly distributed. For other type of channels (such as mobile channels) errors can have different distributions and the estimation of the minimum BLER cannot be directly extrapolated. Another interesting point is that 1% BLER criteria, as it is commonly used during the evaluation of mobile technologies such as LTE, can be in an AWGN channel too relaxed as it would provide unacceptable video quality at the receiver end. While this criterion can be adequate in systems with link adaptation techniques that can request the re-transmission of lost packets, in broadcasting systems without uplink capabilities, requires higher levels of robustness.

Table 43: Minimum estimated BLER for a 100% MDER for different estimated overheads

MCS	Data rate Video Stream (kbps)	Overhead (%)	Minimum BLER for 100% MDER (%)		
			Min. size	**Mean size**	**Max. size**
5	452	0	0.37	0.18	0.11
		33	0.25	0.12	0.07
		66	0.13	0.06	0.04
11	715	0	0.60	0.26	0.14
		33	0.40	0.17	0.09
		66	0.20	0.09	0.05
18	1427	0	0.38	0.17	0.14
		33	0.25	0.12	0.09
		66	0.13	0.06	0.05

B.3.4 Laboratory eMBMS performance results in AWGN channel

Table 44 shows the results of the laboratory experiments for different MCS values. The SNR values reported by measurement in the table are the ones that produce a completely erroneous video sequence. The results are compared with the results reported in reference EBU TR034 that were obtained by simulation with 1% BLER criterion. In addition, the estimated minimum BLER to achieve 100% MDER in the last column assumes average segment size with 33% of overhead. As it can be seen the difference between the measured and simulated results depends on the MCS. While for low MCS values the differences are minimal, these differences increase with the MCS. One possible explanation for this behaviour, especially for MCS 24, is that the sensitivity the devices have similar values to the measured SNR range. However, such hypothesis needs to be further explored and verified with further experiments.

Table 44: BBC Preliminary MPEG-DASH-eMBMS measurements in AWGN channel

MCS Index	Modulation	Data rate Video Stream [kbps]	Simulated EBU TR034* [dB]	Measured BBC** [dB]	Difference	Min BLER for 100% MDER*** [%]
5	QPSK	452	-0.3	-0.1	**0.2**	0.12
9	QPSK	452	3.9	4.2	**0.3**	0.22
11	16QAM	715	4.8	5.2	**0.4**	0.17
16	16QAM	715	9.3	10.9	**1.6**	0.31
18	64QAM	1427	10.7	11.7	**1**	0.12
24	64QAM	1427	16.8	19.8	**3**	0.20

B.4 Conclusions and Outlook derived from eMBMS Performance Measurements

The laboratory results show that a one-to-one mapping between BLER results at the physical layer and video error criteria cannot be done in a straightforward manner. A methodology for the assessment of the video quality in mobile broadcasting systems needs to be defined. The investigations performed in the lab tests in IRT and BBC have shown an initial methodology to measure the received SNR at the receivers without the need of special demodulation software. The investigations also show that the 1% BLER criteria may be too relaxed for practical levels of expected video quality in broadcasting systems, where significantly lower BLER may be needed. Also, the required SNR levels depend strongly on the evaluation criteria, (e.g., ESR5-20 or complete video stream failure). Future topics for further research are outlined below:

1- As a first approach, the ESR5-20 laboratory measurements for eMBMS should be further developed using the derived minimum planning requirements (SNR) and spectrum efficiency as reference. Also including into the evaluations, the possibility of deliver MPEG-DASH video streams.
2- A trade-off between ESR5-20 and BLER/FER should be extrapolated (if possible) based on laboratory measurement and therefore later transferable to field measurements.
3- In this sense, the viability of a reliable measurement methodology beyond the current AWGN measurements must be also investigated for eMBMS.
4- The impact of higher layers and signalling stages on the overall video quality must also be considered.

C LTE eMBMS field trials

This annex shows the results of the trials on LTE eMBMS carried by some of the partners in the 5G-Xcast consortium to evaluate different features of the technology prior Rel'14 standardisation. These tests serve as a basis for future tests that can be done within the 5G-Xcast project. The annex summaries the tests performed within the IMB5 (Integration of Mobile and Broadcast in LTE/5G) project, the FUHF (The Future of UHF Frequency Band) and the BBC trials. This annex also highlights some potential new tests that can be performed given the new functionalities introduced in LTE eMBMS Rel'14.

Reference [112] provides a summary of the key findings from trials and early deployments on LTE eMBMS (before Rel'14) around the world together with technical issues from the network, services and devices perspective.

C.1 IMB5 Project - Munich Field Trial of LTE eMBMS Network for TV Distribution

C.1.1 Background and Motivation of IMB5 Project

In order to investigate the technical capabilities of LTE Broadcast for the provision of TV services over large areas in SFN - similar to today's DTT networks, the Integration of Mobile and Broadcast in LTE/5G (IMB5) project was started in 2014 as a joined activity among representatives of the mobile and broadcast communities: the project was coordinated by Institut für Rundfunktechnik (IRT) and contributed by Nokia, Fraunhofer IIS, University of Erlangen, Rohde & Schwarz, Bayerischer Rundfunk and BMW, and was supported by the Bayerische Forschungs-Stiftung (BFS).

The approach of the project was to study LTE broadcast from a theoretical and practical perspectives in order to get a qualitative and quantitative idea of the potential and limitations of the technology and the necessary requirements to the evolution in future releases. For this purpose, field trials for the LTE eMBMS system were set up in Erlangen and Munich cities of Germany. The eMBMS trial network topology in Munich is presented in Figure 63. The project focused on some limiting aspects of LTE eMBMS Rel'11 that could be enhanced for TV distribution such as CP durations of 16.67 us and 33.33 us, and the capacity limitation for broadcast that could not be more than 60%, setting a limit on the number of High Definition (HD) TV channels that can supported [113].

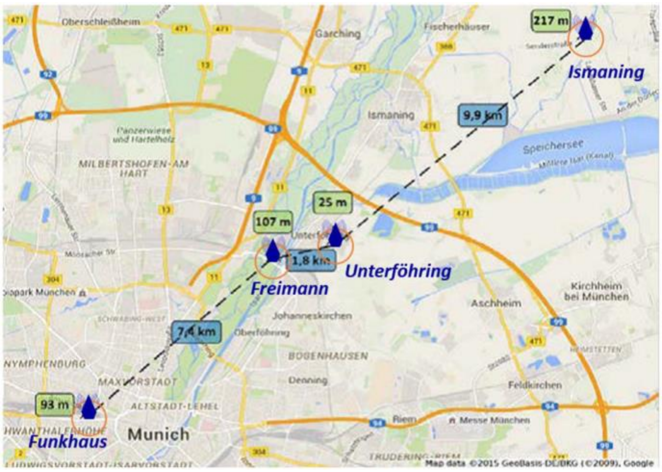

Figure 63: Munich eMBMS trial network topology.

C.1.2 Conclusions derived from IMB5 project and potential tests for 5G-Xcast

In IMB5 project, the performance and limitations of LTE eMBMS Rel'11 network, using a CP duration of 16.67 µs, were investigated in a field trial in Munich, Germany.

The analysed network with its particular transmitter configuration, which is in between a classical broadcast and a typical mobile network, is not tailored for SFN operation with a short CP duration of 16.67 µs. It was demonstrated that the simulation models and methods used in both broadcast and cellular communities could predict the values of the field strength and path loss of each transmitter, eMBMS useful field strength and received power, and SINR with an accuracy that is high enough for the analysis.

Moreover, it was shown that the prediction accuracy can be improved by using simulations models that are calibrated against measurement data. In this sense, the performance of CP durations that are longer than the standardized values of 16.67 µs and 33.33 us were evaluated. It was shown that the extension of the CP duration reduces self-interference and leads to a significant increase in coverage. However, the network gain resulting from the combination of useful signals is rather low in the considered field trial area and a significant improvement due to the extended CP duration is not apparent.

The analysis of the LTE eMBMS network deployed in IMB5 served as an input for the 3GPP study and work items focusing on extending CP duration for TV distribution in LPLT/HPHT networks.

Within 5G-Xcast, the tests carried under the IMB5 project can be extended to evaluate the performance of a SFN with the latest CP length in LTE eMBMS Rel'14 of 200 µs with practical inter-site distances in terrestrial broadcast networks. The identified limitations in Chapter 4 and the numerical evaluations performed in Chapter 4 of this report shown that even longer CP lengths of 200 µs could be beneficial in a HPHT network, hence practical tests could confirm the simulation results.

C.2 FUHF Project - Field measurement of protection ratio between DVB-T2 and LTE

The Finnish project FUHF (The Future of UHF Frequency Band) studied Supplemental Downlink (SDL) technology, which is based on 4G mobile networks, and offers a solution to the problem with the scarcity of frequencies and their capacities. With the help of the SDL technology, the mobile operators could offer a chance to benefit from the TV frequencies to transfer video content to consumers without potentially disturbing the normal TV operations.

The first goal of the field measurements was to develop a test methodology, to validate the test network performance and to assure that the test network did not interfere the DTT reception in the vicinity of the LTE base station. In the later phases, the objective was to measure protection ratios between DVB-T2 and LTE in a real field environment and compare the results to previous laboratory results and to results presented in ITU-R BT.2215-5 (07/2015) Measurement of protection ratios and overload thresholds for broadcast TV receivers Annex 2D *Assessment of LTE 800 MHz Base Station Interference into DVB-T2 Receivers*. The observation from ITU-R BT.2215-5 was that LTE idle mode interference is 10-15 dB worse than in fully loaded situation. The DUTs (Devices Under Test) were the same already measured in the laboratory. In addition, some selective tunable and broadband Master Antenna Television (MATV) products were tested.

Figure 64 shows the channel arrangement for field measurements. The DVB-T test network transmission from Espoo Kivenlahti is on channel 53 and the DVB-T2 transmissions on channels 56 and 60 are commercial multiplexes.

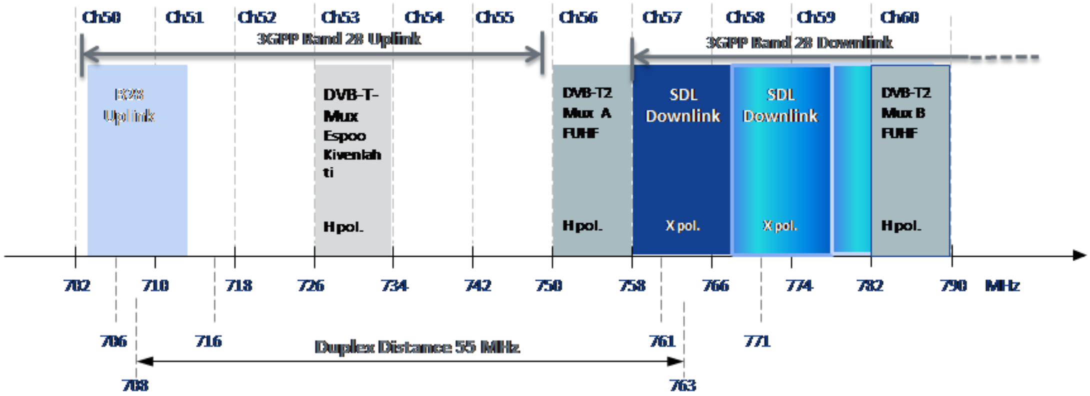

Figure 64: FUHF field measurement cannel arrangement

The DVB-T2 and LTE base station transmission parameters are described in Table 45 and Table 46.

Table 45: DVB-T2 transmitter parameters of FUHF project

Transmitter EIRP	2 kW
Antenna height	100 m
Frequency	786 MHz (channel 60)

Table 46: LTE base station parameters of FUHF project

Number of sectors	3
Tx power	Max 40 W, EIRP 1 kW
Antenna height	49 m
Frequency	DL 758-790 MHz, UL 702-726 MHz

Figure 65 shows the locations of the DVB-T test network transmitter and LTE base stations (eNBs).

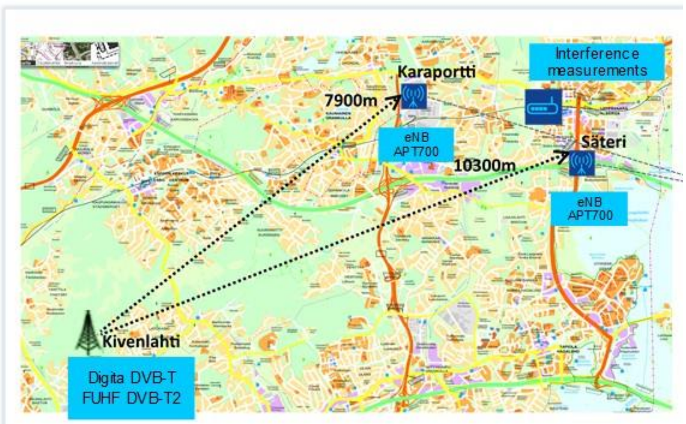

Figure 65: DVB-T and LTE test network transmitter locations in Espoo, Finland

C.2.1 Conclusions from FUHF Project trials and potential tests for 5G-Xcast

The following summarizes results and conclusions from the FUHF project LTE test network field trials:

- Test network was in use for LTE SDL tests in Karaportti area for 15 months and during this time no problems for DTT reception from users were registered by Digita. The nearest houses or buildings with outdoor TV reception antennas installed were at a distance of 300m from the base station, but in the opposite direction than the DTT transmitter. Nearest buildings in the sector where the DTT and LTE base station are in the same direction were at a distance of 600-700 meters.
- Measured protection ratios are in line with the ITU-R BT.2215-5 results (i.e. between the min. and max. values)
- Broadband MATVs are more sensitive to strong LTE base station transmissions than other DTT products (iDTV, STB, PVR etc.). Low-noise mast amplifiers were especially sensitive and could be interfered from the distance of 1100 m.
- The DTT receiving antenna system installation and the related power amplifiers play a key role in how easily the DTT reception is interfered. The receiving antenna system installation is regulated in Finland, and use of integrated mast antenna amplifiers which make the reception system more susceptible to interference is prohibited. The Finnish regulation ensures the protection and coverage of DTT reception and can be seen as an enabler to the potential introduction of more flexible and efficient methods to use UHF TV broadcasting spectrum.

The trials performed in FUHF focused on the potential interference on DTT receivers by SDL technology. With the latest changes in the LTE eMBMS Rel'14 with larger CP length of 200us and downlink only operation, a dedicated eMBMS carrier could form part of a SDL transmission (the supplemental downlink is used to deliver downlink only broadcast services combined with unicast transmissions). These new waveform parameters, or extensions as part of the development in the context of 5G-Xcast with longer CP beyond the 200us, could open the door for utilising existing DTT infrastructure with HPHT to deliver TV services. In this scenario, the interference levels caused by an eMBMS signal transmitted by a HPHT network in both LTE base stations and UEs with unicast could be further topics to be studied by laboratory testing and field trials.

C.3 BBC 4G Broadcast (eMBMS) Trials

BBC Research & Development has been investigating how 4G Broadcast (eMBMS) might be used to improve the delivery of streamed content to mobile devices. Two example use cases have been demonstrated– firstly as part of an app tailored to a specific event (for example at a sports venue), and secondly by connecting the technology seamlessly to BBC iPlayer (the BBC's Internet streaming service that offers both live and catch-up content) to allow viewers to continue watching popular content in congested areas, without the experience being spoilt by buffering.

THE COMMONWEALTH GAMES TRIAL

In the summer of 2014, a trial of 4G Broadcast was carried out as part of BBC R&D's wider public showcase around the Commonwealth Games at the Glasgow Science Centre.

The trial was a collaboration, with BBC R&D providing content and an application, EE providing a network and dedicated spectrum, Huawei supplying equipment and Qualcomm providing software and middleware. The handsets were Galaxy S5s supplied by Samsung. These were off-the-shelf handsets (since they already support eMBMS within the hardware) but with dedicated firmware to enable reception of the broadcast streams.

A 2.6 GHz frequency allocation with a 15 MHz bandwidth was used to provide a private LTE network from a dedicated eNodeB (base station) transmitting the broadcast signals within the confines of the exhibition hall.

Three streams were made available of the BBC's TV channels carrying live action from The Games. The target screen size was 5.1" which meant that standard definition resolution was sufficient and an average video bitrate of 1.3 Mbit/s was used with an MPEG-DASH segment length of 1s. The use of short segments reduces the impact of error extension and ensures that, in the event a segment cannot be recovered at the receiver, the impact to the viewer is minimised.

4G BROADCAST AT THE FA CUP FINAL

Working with the partners from the Commonwealth Games, with the addition of EVS and Intellicore, BBC R&D participated in a trial at the FA Cup Final at Wembley Stadium in London in May 2015.

As well as the live BBC One feed of the Cup Final, the BBC R&D's Stagebox technology we used to deliver an additional two live camera feeds from the outside broadcast area via an IP link. These were then broadcast along with highlights packages. In addition, EVS supplied multi-angle replays to a 'replay zone', allowing users to interactively select the angle of view for incidents of interest during the game.

All of this content, with the addition of real-time statistics, was brought together in a dedicated application written by Intellicore. This ran on a number of specially enabled tablets given out to invited guests. BBC R&D also worked with BBC Sport to seamlessly connect the broadcast streams into the live coverage area within a modified version of the existing BBC Sport application.

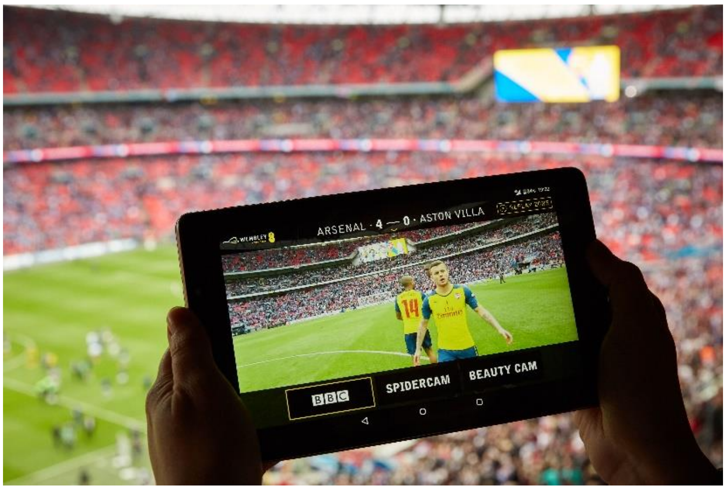

Figure 66: Tablet device with live content from FA Cup final trials of 4G eMBMS

This proved the ability of 4G Broadcast to deliver high-quality content in situations where congestion might not typically allow it and showed the benefits for the user in bringing unicast and broadcast content together in a seamless fashion to give the best possible experience.

C.3.1 Conclusions from the BBC 4G broadcast trials and potential tests for 5G-Xcast

Many of the limitations identified as a result of carrying out these trials, such as the lack of a standardized interface between the content provider and the mobile network, have been addressed by the 'EnTV' initiative under 3GPP Rel' 14.

However, there are a number of areas beyond this which could still be addressed, including support for larger inter-site distances and studying potential improvements in synchronization signals.

As average screen resolutions and handset sizes have increased since the trials took place, the ability to deliver higher resolution (and hence higher bit-rate) content such as UHD is now more pertinent. This makes overall system efficiency even more important meaning there could be a role for techniques such as MIMO, higher order constellations, improved FEC techniques and better frequency re-use in a network.

Finally, there appeared to be a clear benefit in bringing together broadcast and unicast content together in a seamless way for the user, something which 5G-Xcast will work to make easier.

D Spectrum Aspects of LTE PTM deployments

D.1 Spectrum bands of current eMBMS deployments

Several Mobile Network Operators have trialled eMBMS technology and few MNOs have deployed it commercially in 2017. This section describes the trials and the used spectrum bands. The information is mainly derived from GSA document 4G Market and Technology Update LTE Broadcast from January 30, 2017 [55] and Evaluating the LTE Broadcast Opportunity [56].

Telstra trialled LTE-Broadcast live on a commercial network in October 2013. The system demonstrated live video and large file delivery. It was deployed by Ericsson and Qualcomm Labs' LTE Broadcast SDK and Middleware was used in the user equipment. In 2013, Telstra had commercial LTE service on 1800 MHz band. Telstra plans to begin commercial LTE Broadcast services in 2017 with a country-wide coverage in 2018. The technology partners in the commercial operation are Ericsson and Expway. Specific Samsung devices are supported. Telstra has LTE services on bands 700, 1800, and 2100 MHz.

Claro and NET conducted LTE broadcast trials in Brazil during Rio Open tennis tournament Rio de Janeiro in Feb 15-21, 2016. The trials were carried out with Ericsson, Qualcomm, and Samsung. Claro has LTE on 2600 MHz band.

China Mobile showed live LTE Broadcast in 3G/4G Summit in September 2014. The demonstration partners were Ericsson, Qualcomm, and LG. In 2014, China Mobile had LTE services on bands 1900, 2300, and 2500 MHz.

China Telecom deployed a pre-commercial LTE eMBMS network in Nanjing and demonstrated it in Mobile Internet Forum in Jun 2014. China Telecom had LTE services on 2300 and 2500 MHz band in 2014.

China's first commercial LTE Broadcast deployment came from China Unicom in Aug 2017. At the launch of the service, the passengers of Hainan Island high-speed train can receive the LTE Broadcast service as a part of the Gigabit LTE network. The network is provided by Ericsson. China Unicom has LTE on 1800 and 2500 MHz bands.

Orange France demonstrated LTE Broadcast at France Open tennis tournament in May 2014. The network was from Alcatel-Lucent/Expway, multi-cast middleware from Expway and devices from Sequans. The demonstration was with four live channels at 2.5 Mbps in 6 MHz downlink channel in the 2600 MHz band.

TDF trialled the concept Tower overlay over LTE-Advanced (LTE signal from a HPHT DTT network) in Paris from Eiffel tower and RAI in Aoste Italy in April 2015. In Tower overlay over LTE-Advanced the LTE signal is transmitted using DVB-T2's Future Extension Frames which enable simultaneous transmission of DVB-T2 and LTE data streams. The technology providers were TU Braunschweig, GatesAir, IRT, and Expway. The French transmission was on TV UHF channel 54 (738 MHz) and Italian transmission as a SFN network of two transmitters on channel 53 (730 MHz).

Vodafone Germany trialled LTE Broadcast in Borussia Mönchengladbach football stadium in February 2014. The network was provided by Ericsson and the handsets by Qualcomm and Samsung. Vodafone Germany had LTE services on 800 and 2600 MHz in 2014.

Bayerischer Rundfunk trialled LTE Broadcast on four sites covering a 200-square kilometer area in Munich in July 2014. The service was on 3GPP LTE band 28 (FDD, 706 to 716 MHz uplink, 761 to 771 MHz downlink). The network was provided by Nokia.

China Mobile demonstrated LTE Broadcast in Hong Kong in September 2014. The network provided by Ericsson and the devices by LG and Qualcomm. In 2014, China Mobile had LTE services on 1800, 2300, and 2600 MHz bands.

Telecom Italia Mobile showed LTE Broadcast in the AC Milan football match in Milano in Apr 2015 and in World Expo in Milano in October 2015. AC Milan trial was with Huawei and Expway. The World Expo pilot was carried out in collaboration with Ericsson, RAI, Qualcomm, and Samsung. At the time of trials, Telecom Italia Mobile had LTE service on 800, 1800, and 2600 MHz bands.

Softbank tested LTE Broadcast with Intellicore, Sharp, and Qualcomm in Fukuoka baseball stadium in September 2016. Softbank had LTE services on 700, 900, 1800, 2100, 2500, and 3500 MHz bands in 2016

KPN trialled LTE Broadcast with Ericsson, Samsung, and IBM during an Ajax football match in Amsterdam in May 2014. In 2014, KPN had LTE service on 800, 1800, and 2600 MHz bands.

Globe demonstrated LTE Broadcast with Huawei in Globe Innovation Forum in Philippines in September 2014. Globe had LTE service on 1800 and 2500 MHz bands in 2014.

Smart trialled LTE Broadcast with Huawei on 2100 MHz band in Philippines in November 2013 and with TV5 and Cignal Digital TV in February 2014. Smart had LTE service on 850, 1800, and 2100 MHz bands in 2013-2014.

Polkomtel demonstrated LTE Broadcast with Ericsson, Samsung, and Polsat at a World Volleyball Championship match in Warsaw in August 2014. Polkomtel had LTE service on 1800 MHz band in 2014.

Megafon tested LTE Broadcast with Huawei on 2600 MHz band in Russia in September 2014.

MTS trialled LTE Broadcast with Ericsson and Qualcomm in Novgorod, Russia in October 2015. MTS had LTE service on 800, 1800, and 2600 MHz bands in 2015.

SingTel demonstrated LTE Broadcast with Ericsson at the South East Asian Games in Singapore in June 2015. Singtel had LTE services on 900, 1800, and 2600 MHz bands in 2015.

Korea Telecom launched the world’s first commercial LTE Broadcast service with Samsung in South Korea in January 2014. Korea Telecom had LTE Service on 850, 1800, and 2100 MHz bands in 2014. The service covers subway lines and baseball stadiums. LTE Broadcast service is supported by high-end Samsung devices powered by Expway middleware.

Spain Vodafone trialled LTE Broadcast with Expway, Quickplay and Thomson at a Valencia football match in May 2015. In May 2015, Vodafone had LTE service on 800, 1800, and 2600 MHz bands.

Turkcell demonstrated LTE Broadcast with Ericsson in a basketball match in Istanbul in May 2016. Turkcell had LTE service on 800, 1800, 2100, and 2600 MHz bands in 2016.

Etisalat trialled LTE Broadcast with Alcatel-Lucent/Expway in Abu Dhabi, United Arab Emirates in March 2014. Etisalat had LTE service on 1800 and 2600 MHz bands in March 2014.

EE demonstrated LTE Broadcast with BBC, Qualcomm, Huawei, plus EVS, and Intellicore in Commonwealth Games in Glasgow in May 2014 and at FA Cup final football match at Wembley Stadium in May 2015. EE had LTE service on 1800 MHz band in May 2014 and additionally on 2600 MHz band in 2015.

AT&T trialled LTE Broadcast with Ericsson, Qualcomm, ESPN, MobiTV, and Samsung at Ohio State Buckeyes American College football match in Arlington, Texas in January 2015. AT&T had LTE service on 700, 850, 1700, and 1900 MHz bands in January 2015, and at SuperBowl in February 2015.

Verizon opened commercial LTE Broadcast service for IndyCar mobile app in the US in April 2016. Verizon has LTE service on 700, 1700, and 1900 MHz bands.

MobiFone trialled LTE Broadcast in Hanoi, Danang and Ho Chi Minh city in July 2016. MobiFone has LTE radio license on 1800 MHz band.

LTE Broadcast trials have also been conducted by Vivo (Telefonica Brazil), Canada Bell Mobility, T-Mobile in Germany, Hong Kong PCCW (CSL) with Huawei at the Hong Kong Rugby Sevens, RJIL India with Samsung, Expway, and Marvell, Meo in Portugal with Huaway, Portugal Vodafone, Three in the UK.

RJIL has launched a commercial LTE Broadcast service since April 2017. Their network is powered by Expway and Samsung and on the clients run Expway and Qualcomm middleware. LTE broadcast is used mainly to cover the Indian Premier League Cricket. RJIL operates its LTE services in the bands: 2300MHz and 1800MHz

Commercial LTE Broadcast services have been introduced by Verizon in the US and Korea Telecom in South Korea. A large portion of the major mobile network operators have gained practical experience with LTE Broadcast. All major network vendors offer eMBMS products, and a few companies, especially Expway, are targeting at the LTE Broadcast market. Qualcomm has a strong support of LTE Broadcast in the high-end chipsets and commercial end user equipment is available, primarily from Samsung, in the areas where the LTE Broadcast services are offered. Few of the LTE Broadcast trials have been carried out on the current UHF broadcast bands that would indicate the LTE Broadcast taking over the existing broadcast services. Most of the pilots have been on the capacity LTE bands, like 1800 and 2600 MHz, and locations have been on a stadium at sports or performing arts event. Reasons for this are publicity, content availability, and easy trial management with often required special end user equipment.

D.2 5G spectrum

In the EU the allocation and management of radio spectrum are administered by National Regulatory Authorities (NRAs), within a harmonised EU regulatory framework[8] and taking into account the decisions taken by ITU World Radiocommunication Conferences (WRC). This section describes the current status of spectrum for 5G in Europe. European Commission Radio Spectrum Policy Group (RSPG) recommended 700 MHz, 3.4-3.8 GHz, and 26 GHz bands as the 5G pioneer bands in Europe [57]. The following subsections go through announcements and documents following the same band selection. The NRA of the UK, Ofcom was the first European regulator to confirm the 5G pioneer bands, and its announcement is used as an example of European NRA action in 5G spectrum allocation. CEPT has established its own 5G roadmap[9].

D.2.1 700 MHz

The 700 MHz band was confirmed as a primary mobile allocation in Region 1, which includes Europe, by the ITU WRC in 2015. The WRC-15 further concluded that a wider

[8] https://ec.europa.eu/digital-single-market/node/118

[9] https://cept.org/ecc/topics/spectrum-for-wireless-broadband-5g

review of 470-960 MHz should be considered at WRC-23 [58]. RSPG opinion states that 700 MHz is the pioneer band for 5G below 1 GHz. The main purpose of the band is to provide nationwide and indoor 5G coverage [57]. In its statement, Ofcom notes that the UK is planning to clear 700 MHz and make it available for mobile data [59].

According to the EU decision[10] the 700 MHz band will be cleared from DTT and made available for mobile use by 2020 with a possible extension until 2020, where justified. The paired 2 x 30 MHz FDD spectrum will be licensed under the harmonised technical conditions whereas NRAs have the flexibility to decide how to use the guard band and the duplex gap. In addition, there will be differences in terms of how Public Protection and Disaster Recovery (PPDR) are accommodated. As an example, France is considering a dedicated 700 MHz band allocation for PPDR while the UK will have PPDR using commercial networks in 700 MHz band. The countries, which allocate the 700 MHz in 2017 or 2018, will have LTE networks rather than 5G in the band.

D.2.2 3.4-3.8 GHz

The band 3.4-3.8 GHz is harmonized for mobile broadband under decisions 2008/411/EC and 2014/247/EU [60] in Europe. According RSPG, 3.4-3.8 GHz band is the primary band for 5G networks in Europe before 2020. RSPG hopes that this band will create the leadership for Europe in global 5G deployments [57]. Ofcom has cleared 3410-3480 MHz and 3500-3580 MHz for mobile networks. 3605-3689 MHz is also assigned to mobile communications as shared spectrum. Ofcom closed a consultation about the statement and consultation on Ofcom’s intention to expand spectrum access for mobile services in the 3.6-3.8 GHz band in September 2017 [61].

EU countries have very different spectrum licenses on 3.4 to 3.8 GHz, currently. They also have different possibilities and political and regulatory plans in terms of clearing the band. Due to this, it is possible that the EU countries will significantly differ how the band is taken to mobile use. A few countries clear the band and have nation-wide exclusive licenses. A few countries can clear the band in large extent but need to protect e.g. satellite ground stations. A few countries will have static sharing between mobile and several current license holders. A few countries will have regional licenses so that there will be regional sharing between mobile license holders on the same band. A few countries will have sharing in time domain by utilizing Licensed Shared Access or similar dynamic sharing tools. A few countries will encourage sub-licensing of nation-wide or regionally licensed spectrum for specific properties or events. In the US, FCC and Wireless Innovation Forum carry out extensive specification work how 3550-3700 MHz can be taken to more efficient use by utilizing dynamic spectrum access under the concept name Citizen’s Broadband Radio Service (CBRS). CBRS may impact European deployments on 3.4-3.8 GHz band, as well.

D.2.3 26 GHz and above

WRC-19 agenda item 1.13 identifies the following bands for IMT-2020 within the frequency range 24.25-86 GHz: 24.25-27.5, 31.8-33.4, 37-43.5, 45.5-50.2, 50.4-52.6, 66-76, and 81-86 GHz. The RSPG recommends the 24.25-27.5 GHz (26 GHz band) as a pioneer band for 5G above 24 GHz. Additionally, RSPG identifies the bands 31.8-33.4 and 40.5-43.5 GHz as viable option for 5G in the future. Ofcom supports the 26 GHz band as the priority millimetre wave band for global harmonization.

D.3 Broadcast bands

The broadcast bands in Europe are collected in [62]. The document refers to [63] and especially to the allocations and relevant footnotes for Region 1. The footnotes are

[10] Decision (EU) 2017/899 - http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017D0899

referred here in the form "[5.190]". The broadcast bands are compared to 5G pioneer bands in Figure 67 and in Table 47. When 5G pioneer bands are compared to the broadcast bands, it can be noted that 700 MHz band overlaps with the terrestrial broadcast bands and that 3.4-3.8 GHz and 26 GHz bands have satellite broadcast bands in the neighbouring bands.

Table 47: Spectrum allocations for broadcast

Service	MHz	Footnote [63]	Service	GHz	Footnote [63]
FM radio	87.5-100	5.190	Sat L-band	1.452-1.492	5.208B, 5.341, 5.342, 5.345
FM radio	100-108	5.194	BSS	2.520-2.655	5.413, 5.416, 5.339, 5.412, 5.418B,5.418C
VHF TV	174-216	5.235, 5.237	BSS	2.655-2.670	5.208B, 5.413, 5.416
VHF TV	216-223	5.235, 5.237, 5.243	BSS	11.7-12.5	5.492, 5.487, 5.487A
VHF TV	223-225	5.243, 5.246, 5.247	BSS	21.4-22	5.208B,5.530A, 5.530B,5.530D
UHF TV	470-694	5.149, 5.291A, 5.294, 5.296, 5.300, 5.304, 5.306, 5.311A, 5.312	BSS	40.5-42.5	5.547, 5.551H, 5.551I
	694-790	5.300, 5.311A, 5.312]			
	790-862	5.312, 5.319			

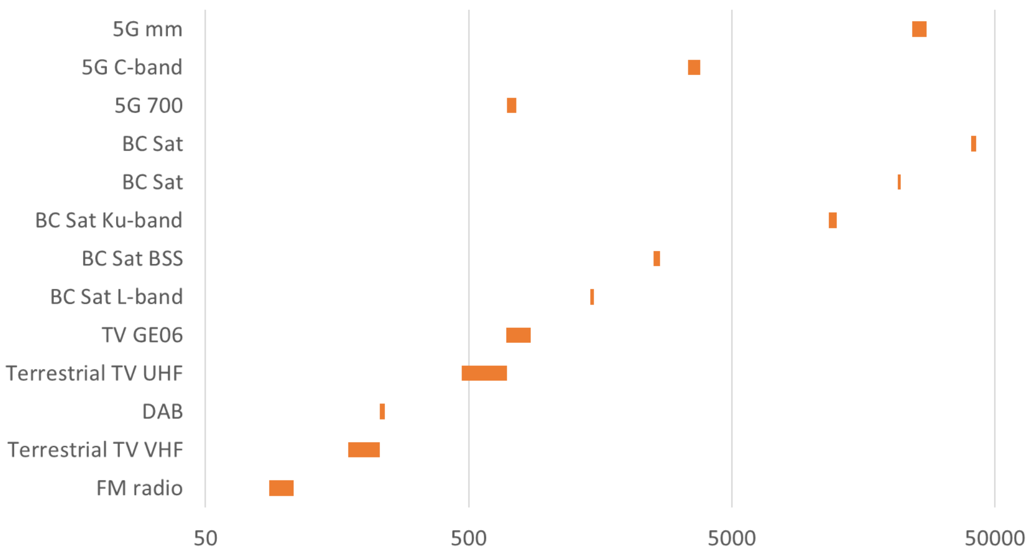

Figure 67: 5G pioneer bands and broadcast bands

D.4 Recent 5G-Xcast related proposals

5G-Xcast studies the following spectrum related concepts: Licensed Shared Access (LSA) in section D.5.2, US 600 MHz incentive auction in section D.4.1, Standalone eMBMS network in section D.4.2, WideBand reuse 1 in section D.4.3, and Supplemental DownLink (SDL) in section D.4.4. The spectrum bands of these proposals are compared to the 5G pioneer bands in Figure 68.

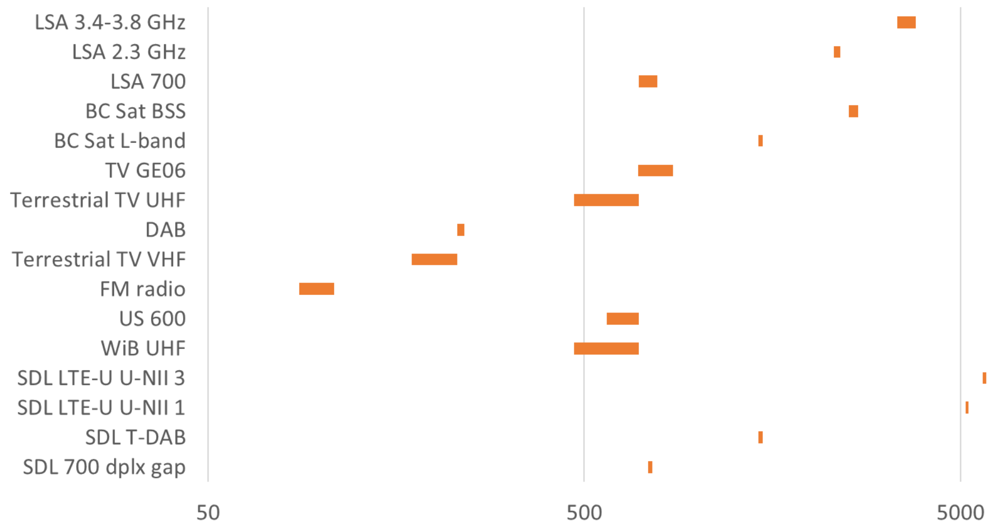

Figure 68: Selected 5G-Xcast spectrum proposals

D.4.1 US 600 MHz

FCC carried out incentive auction to rearrange the local broadcasters, services and free capacity for wireless broadband so that the broadcasters are reimbursed by the new users in the UHF and high-VHF TV bands in the US. The auction resulted in 70 MHz for licensed use and 14 MHz unlicensed spectrum. The broadcasters benefited 10.5 billion USD and US government more than 7 billion USD. The process of receiving spectrum usage rights from broadcasters was called reverse auction and the license allocation for the new users was called forward auction. The licensed 70 MHz is referred as 600 MHz Band. It contains 663-698 MHz uplink and 617-652 MHz downlink band. The duplex gap is left at 652-663 MHz. Uplink and downlink bands are divided into seven 5 MHz channels [64]. The successful outcome of the US incentive auction means that there will be commercial 600 MHz network and end-user devices on the market.

D.4.2 Standalone eMBMS network

3GPP Technical report TR 36.743 discusses the topic Standalone dedicated MBSFN/eMBMS carrier. The scenario would enable a broadcaster to have an own eMBMS dedicated frequency channel allocation and network without providing other 3GPP services [65].

D.4.3 WiB

5G is expected to provide capabilities in the near future to meet the requirements of a wide range of use cases, including large-scale media unicast/multicast/broadcast distribution. The development of 5G will offer new opportunities beyond the capabilities of eMBMS or LTE broadcasting, which has already been enhanced in 3GPP Rel’ 14 including multiple requirements spurring from the cooperation with the broadcasting industry. 5G is adopting new features for wideband operation with large bandwidths (BWs) to meet the multi-Gbps data rate requirements of enhanced mobile broadband (eMBB). Support in 3GPP for a minimum large bandwidth of 100 MHz has already been adopted for operation below 6 GHz, which will be implemented thanks to a wide scalable numerology. Moreover, bandwidth could be further extended by the aggregation of multiple carriers.

The potential implementation of wideband operation for broadcasting breaks with the traditional concept of channel allocation in Digital Terrestrial Television (DTT) and may bring significant advantages in terms of power efficiency. With frequency reuse factor > 1, the available frequency resources (RF channels) are orthogonally distributed across multiple stations. This fact limits available spectrum per transmitter area, and leads to the necessity of using high capacity transmission modes to compensate for the limited amount of spectrum. Reception of such modes requires very high SNR thresholds and limits resilience against interferences. Thus, stations operating in the same frequency need to be positioned far away (i.e. large reuse distance). As an example, the Geneva plan GE06 results in an average frequency reuse of around 5-6 in Europe. Since the GE06 plan has been initially established the use of single-frequency DTT networks is also increasing in Europe.

High Power High Tower (HPHT) is the general topology in DTT networks, since high capacities can only be obtained by transmitting high power. Power grows exponentially with capacity which in turn supposes a high operational cost.

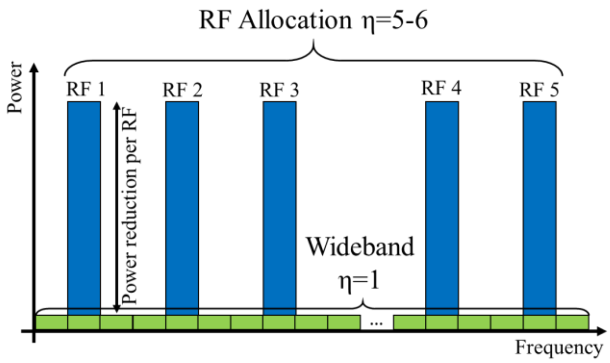

Figure 69: Frequency and power allocation with current DTT systems and Wideband Broadcasting

Wideband Broadcasting can result in a more power-efficient approach where potentially all RF channels from all transmit stations can be used. The concept is depicted in Figure 69. As an illustrative example, consider the terrestrial broadcast UHF band in Europe (470-694 MHz) comprising 28 multiplexes in total (i.e., 8 MHz RF channels). With a frequency reuse factor of around 5-6 and using 5 multiplexes (8 MHz RF channels), a capacity of about 200 Mbps can be achieved with the commonly used DVB-T2 mode 256QAM 2/3 (5.33 bps/Hz). On the other hand, a similar capacity could be obtained with QPSK 1/2 (about 1 bps/Hz) employing the whole frequency band (28 multiplexes). Table 48 shows a comparison of these two transmission modes. 256QAM 2/3 requires about 16-18 dB higher SNR threshold than QPSK 1/2 (17 dB in the Table). This represents an opportunity of transmitting about 17 dB less power (50 times) per 8 MHz channel although using more RF channels per station (28 instead of 5), leading to a total transmit power saving of about 90%. Note that the ATSC 3.0 standard already provides spectral efficiencies closer to Shannon limit implementing transmission modes with even negative SNR thresholds, so leading to increased savings.

Table 48: Spectral efficiency, SNR threshold and potential power saving comparison between high and low rate transmission modes

Transmission Mode	Spectral Efficiency	SNR Threshold	Power per RF channel	Number of RF channels	Total Power

256QAM 2/3	5.33 bps/Hz	≃17 dB	50 W	5	50 * 5 = 250 W
QPSK 1/2	1 bps/Hz	0 dB	1 W	28	28 * 1 = 28 W

Whether the fundamental advantages of wideband operation can be implemented in a current network or not will mainly depend on the possibility of providing the same coverage levels as the current DTT networks. Most DTT networks are designed for roof-top reception on the basis of interference-limited coverage. Decreasing frequency reuse down to 1 may result in coverage limitations due to co-channel interference (see Figure 70). These may be coped with by using ultra-robust transmission modes with SNR less than 0 dB but resulting in very low data rates. Under certain conditions, the implementation of Successive Interference Cancellation (SIC) processes to cancel interfering signals that limit the coverage in the frequency reuse 1 scenario may improve coverage performance reaching the same coverage levels as in current DTT system at the expense of increased receiver complexity.

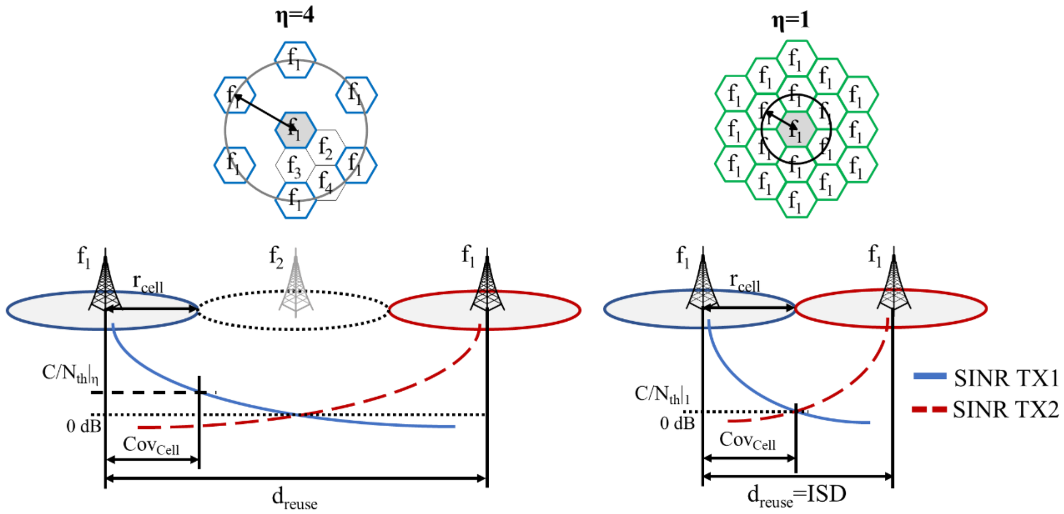

Figure 70: Effect of the frequency reuse in decreasing SINR and coverage area.

The feasibility of the Wideband Broadcasting concept and the technical enablers that would allow maintaining the coverage area, the technical viability and implementation of SIC as well as other spectrum related aspects should be the focus of further studies. WideBand reuse one could be used between TV transmission (like wireless microphones and TVWS devices) to create a wideband carrier, or it could be used as a 100 MHz contiguous band to carry all terrestrial TV channels instead of 8 MHz multiplexes.

D.4.4 Supplemental Downlink (SDL)

The ECC DEC (15)01 [66] specifies the MFCN harmonized frequency arrangement in the band 694-790 MHz as a paired frequency arrangement (FDD 2x30 MHz) and an optional unpaired frequency arrangement (SDL), zero or up to four block(s) of 5 MHz for SDL. ECC Report 239 studies the interference between SDL and PPDR UL [67]. ECC DEC (13)03 [68] harmonises the use of the 1452-1492 MHz for MFCN SDL. The compatibility studies and out-of-band emission limits can be found in ECC reports 227 [69] and 202 [70], respectively. 3GPP technical reports for 700 MHz and 1.4 GHz SDL can be found in documents 36.895 [71] and 37.814 [72], respectively. The coexistence of SDL and DTT on UHF (470-790 MHz) has been studied in [73]. In addition to these, unlicensed LTE was specified for SDL use in the beginning, see Section Unlicensed LTE below.

D.5 Spectrum sharing in broadcast and multicast context

Spectrum sharing can be divided in exclusive spectrum use, i.e. no spectrum sharing, static sharing with radio licenses, dynamic sharing using electronic control like geolocation database or listen before talk equipment, and public access. From global perspective, practically all spectrum bands are shared. Regionally or per country, there can be exclusively allocated spectrum bands, but even then, more than 50 % of spectrum is shared by different type of users. By far, the most common way of spectrum sharing is static sharing. Mostly but not always, radio communication using exclusive radio licenses is protected from harmful interference by the radio administration. License-exempt use is not interference protected, and dynamic spectrum sharing can be used to provide coordination for both interference protected and unprotected radio spectrum. Between licensing models and sharing types, we can recognize different ways of coordination. Radio licenses are the typical way of spectrum coordination for a radio administration. On certain bands, the radio licenses may be required but the mutual interference coordination is carried out by the industry. For example, when PMSE bands require a license, the coordination can be industry coordinated with the exception of the very large events. Listen before talk equipment can coordinate transmissions locally. One of the most common uncoordinated spectrum use for general public is Industrial Scientific and Medical (ISM) band, which is used, for example, by WiFi and Bluetooth. Figure 71 shows the relationship of different licensing, sharing, and coordination models in spectrum management. A typical LSA spectrum sharing profile: licensed, protected from other but higher priority users, secondary, database coordinated dynamic sharing is marked with bold font in the figure.

Licensing	Interference protection	Priority	Coordination	Sharing
Licensed	Protected	Primary	NRA coordinated	Exclusive
License-exempt	**Protected from other but higher priority users**	Co-primary	***Database coordinated***	Static sharing
	Protected from lower priority users	**Secondary**	Listen before talk	***Dynamic sharing***
	Not protected	Unspecified	Uncoordinated	Public access

Figure 71: Classification of spectrum sharing, typical LSA profile in bold font

There are two streams of dynamic spectrum management frameworks developed during this decade. One contains the centrally managed systems, including TV White Space (TVWS), Licensed Shared Access (LSA), and Citizen's Broadband Radio Services (CBRS). The other one has dynamic spectrum sharing systems without central coordination: Unlicensed LTE (LTE-U), Licensed Assisted Access (LAA), and MulteFire. The following sections introduce these dynamic spectrum sharing systems with a standardization and regulation perspective.

D.5.1 TVWS

Terrestrial TV networks are mainly Multiple Frequency Networks (MFN), meaning that the neighbouring transmitters use different frequencies in order to avoid interference in the TV receivers. In Europe, DVB-T2 networks support SFN, where neighbouring transmitters transmit on the same frequency. In most European countries, where DVB-T2 SFN networks are deployed, the main transmitters still operate as MFN relative to other main transmitters. The terrestrial TV frequency plan in Europe follows International Telecommunications Union Radiocommunication sector (ITU-R) GE06 [74] plan. The original allotments define geographically areas and allowed broadcast frequencies in each allotment. The frequencies, which are not used in the allotments, are called TV White Space. The final step of the transition was called Analog Switch-Off (ASO). Federal Communication Commission (FCC) adopted rules for TVWS in the US in November 2008 [75], and amended them in 2010 [76] and 2012 [77]. Infocomm Development Authority of Singapore issued the regulatory framework for TVWS in June 2014 [78]. Ofcom (UK) released the TVWS regulations in 2015 [79].

Finnish WISE project [WISE TUAS] measured performance and interference of Wimax-TVWS base station installation on a broadcast mast at 110 m height. The broadcast antennas were at 313 m antenna height [80]. The conclusions were:

Leakage level from the TV transmitter to BTS receiver is not a problem with 210 m vertical distance. In the downlink within around 2 km, the TV signal level is so high in the CPE receiver that it clips the AD converter. A bandpass filter or an attenuator is needed in the CPE. In 90 m, the uplink receiver of the BTS has a significantly increased noise level caused by distant TV stations. Sector antennas and optimization of the base station antenna height are recommended work on this issue.

In order to evaluate the link quality of a TV mast BTS installation, the following measurements or computations are required: BTS transmitter White Space channels and maximum power on each channel, BTS receiver noise level on the White Space channels, CPE transmitter White Space channels and maximum power on each channel, CPE receiver noise level on the White Space channel, CPE receiver noise level on TV channels, and Path loss between the receiver and transmitter

The optimal BTS antenna height can be estimated by evaluating interference from the TV transmitters above (higher position has more interference), increased noise level from the distant TV transmitters (higher position has more interference), and increased path loss (lower position has more path loss).

Meld Technology produces TVWS equipment for pico-broadcasting [81]. In principle, any broadcast transmitter equipment can operate as a TVWS device. Depending on the national regulation the transmitters may have to be under a control of a TVWS geolocation database.

D.5.2 Licensed Shared Access (LSA)

European Conference of Postal and Telecommunications Administrations (CEPT) has specified technical and operational guidelines for implementing Licensed Shared Access (LSA) on 2.3-2.4 GHz [82] and on 3.6-3.8 GHz [83] frequency range. European Telecommunications Standards Institute has produced architecture and procedure specification for LSA [84]. ETSI plans to extend the original LSA licensing scheme with temporary spectrum access [85]. 3GPP carried out a study on OAM support for Licensed Shared Access [86].

D.5.3 LSA for local and temporary networks

ETSI RRS [92] has started a work item to study feasibility and technology for local high-quality wireless networks to access spectrum temporarily on a shared basis. The objective of the work is to identify how the current sharing frameworks like LSA and CBRS fit for this purpose. A comparison of CBRS and LSA for local temporary use can be found in [93].

D.5.4 Citizen's Broadband Radio Service (CBRS)

FCC opened 3.5 GHz band for Dynamic Spectrum Access with Report and order, and its amendment [87] and [88] in the US. The code for the FCC regulations is in Part 96 of Title 47 the U.S. Code of Federal Regulations [89]. Wireless Innovation Forum has published the required technical specifications to operate CBRS Spectrum Access System commercially in [90]. CBRS Alliance promotes the use of CBRS for LTE based communication [91].

D.5.5 Unlicensed LTE

LTE-U started the series of unlicensed LTE studies in 3GPP Rel' 12 [94], [95]. The coexistence tests were defined with SDL emphasis by LTE-U Forum [96]. 3GPP specified LAA for downlink operation in Rel' 13 [97] and enhanced LAA (eLAA) for uplink operation in Rel' 14. LAA and eLAA are deployed in CBRS according to [98]. Related LTE-WLAN Aggregation was part of Rel' 13 [99]. MulteFire frees the unlicensed LTE from the licensed wide-area network dependency [100].

D.5.6 Generic spectrum management trends

With 5G, the clear new mobile spectrum trends are the need for wider bandwidths in the order of magnitude of 100 MHz and the use of the spectrum bands above 24 GHz. GSMA suggests that MNOs have interest also in unlicensed bands complementing the licensed spectrum.

Due to current licenses in Europe, although widely harmonized bands and licensing conditions are strongly favoured, for example on 3.4 – 3.8 GHz 5G pioneer band, it is expected that the licensing conditions will differ from country to country in Europe.

Surging video traffic in all radio data networks, not limited to mobile networks, increases demand of spectrum in all radio networks. This situation improves the flexibility to accept also shared spectrum use. An example is Finnish Defense Forces idea to change spectrum use priorities based on the emergency status in the society [101].

A new spectrum opportunity is emerging by spectrum brokering. The FCC revisited rules for CBRS in 2016, and introduced the light-touch leasing process to enable secondary markets for the spectrum use rights held by PAL licensees [102]. Under the framework, no FCC oversight is required for partitioning and disaggregation of PAL licenses, and PAL licensees are free to lease any portion of their spectrum or license outside of their PPA. A study about spectrum broker for temporary licenses can be found in [103]. In addition to CBRS light-touch leasing, spectrum brokering will be useful for allocating spectrum for e.g. LSA "local and temporary high-quality networks", Special Events, and R&D licenses.

E LTE-Advanced Pro Turbo-decoding performance

E.1 Introduction

This annex compares the performance of LTE-Advanced Pro turbo-decoder with two decoding algorithms. The first algorithm is the true a-posteriori probability decoding and the second algorithm (Max-Log-MAP) reduces the computational complexity by replacing the $\log\{\sum_i \exp[a_i]\}$ by $\max\{a_i\}$ at the expense of a performance degradation.

The MCS selected from the 3GPP LTE-Advanced Pro specifications are based on table 7.1.7.1-1 of TS 36.213, which does not include 256QAM constellation. A representative set of MCS is selected, in particular, MCS 5 & 9 correspond to QPSK, MCS 11 & 16 correspond to 16QAM and MCS 18 & 24 correspond to 64QAM. The turbo-decoding algorithms are evaluated in AWGN, i.i.d. Rayleigh and TU6 channels as detailed in A.2.1.2.

E.2 AWGN channel model

The BLER vs. SNR (dB) performance in AWGN channel is presented in Figure 72. The system parameters used in this simulation are the same as in A.5.1 for MBSFN with 1.25 kHz subcarrier spacing. The performance degradation in dB at BLER 0.1% is showed in Table 49 where the loss ranges from 0.25 to 0.57 dB.

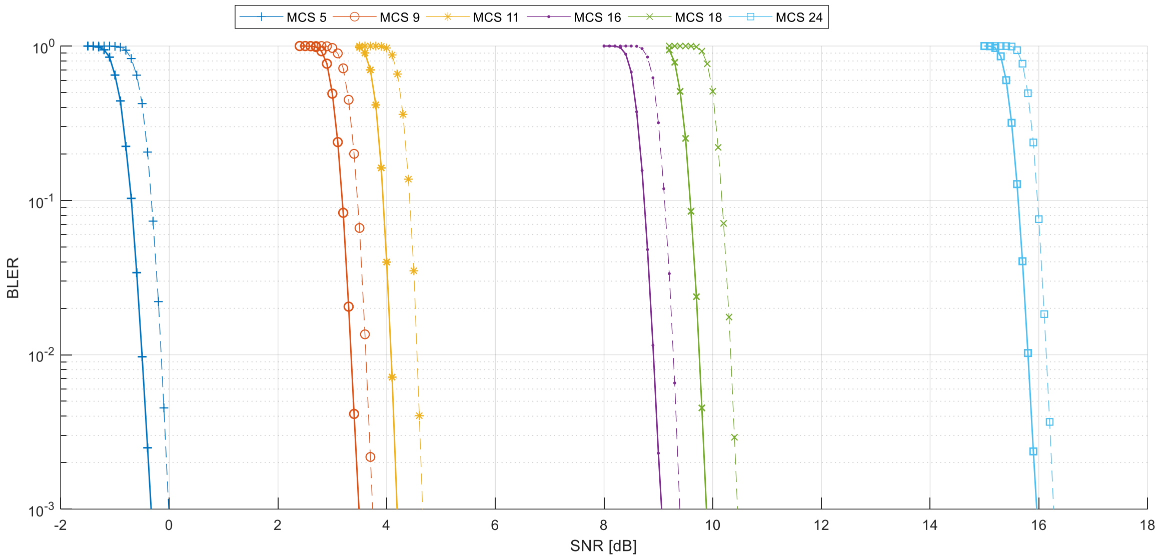

Figure 72: LTE-Advanced Pro Turbo-decoding performance comparison in AWGN channel. Solid and dashed lines show the performance of true a-posteriori decoding and Max-Log-MAP algorithms, respectively.

Table 49: Performance degradation in dB of the two turbo-decoding algorithms evaluated for LTE-Advanced Pro in AWGN channel.

	MCS 5	MCS 9	MCS 11	MCS 16	MCS 18	MCS 24
Degradation in dB	0.32	0.25	0.47	0.33	0.57	0.30

E.3 i.i.d. Rayleigh channel model

The BLER vs. SNR (dB) performance in i.i.d. Rayleigh channel is presented in Figure 73. The system parameters used in this simulation are the same as in A.5.1 for MBSFN with 1.25 kHz subcarrier spacing. The performance degradation in dB at BLER 0.1% is showed in Table 50 where the loss ranges from 0.46 to 0.63 dB. Here, it is interesting to point out that MCS 11 outperforms MCS 9 which provides lower spectral efficiency.

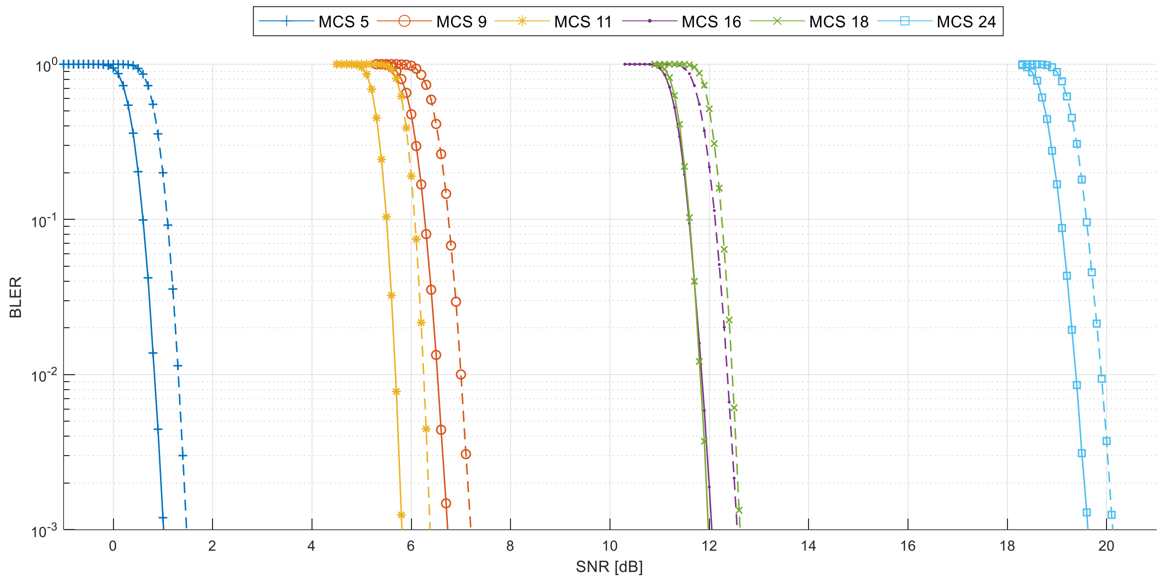

Figure 73 : LTE-Advanced Pro Turbo-decoding performance comparison in i.i.d. Rayleigh channel. Solid and dashed lines show the performance of true a-posteriori decoding and Max-Log-MAP algorithms, respectively.

Table 50: Performance degradation in dB of the two turbo-decoding algorithms evaluated for LTE-Advanced Pro in i.i.d. Rayleigh channel

	MCS 5	MCS 9	MCS 11	MCS 16	MCS 18	MCS 24
Degradation in dB	0.46	0.46	0.57	0.51	0.63	0.50

E.4 TU6 channel model

The BLER vs. SNR (dB) performance in TU6 channel with a user speed of 130 km/h at 700 MHz of carrier frequency is presented in Figure 74. The system parameters used in this simulation are the same as in A.5.1 for MBSFN with 15 kHz subcarrier spacing with CFI=1. The performance degradation in dB at BLER 0.1% is showed in Table 51 where the loss ranges from 0.52 to 0.65 dB. Here, it is interesting to point out that for true a-posteriori probability decoding MCS 11 and MCS 18 outperform MCS 9 and MCS 16, respectively, which provide lower spectral efficiency.

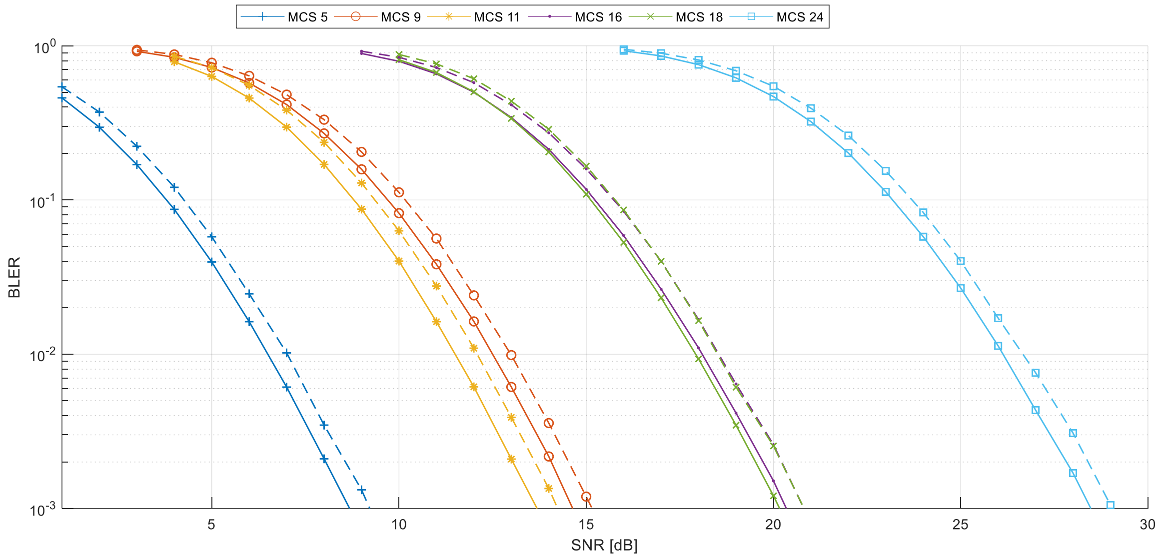

Figure 74 LTE-Advanced Pro Turbo-decoding performance comparison in TU6 channel. Solid and dashed lines show the performance of true a-posteriori decoding and Max-Log-MAP algorithms, respectively.

Table 51: Performance degradation in dB of the two turbo-decoding algorithms evaluated for LTE-Advanced Pro in TU6 channel

	MCS 5	MCS 9	MCS 11	MCS 16	MCS 18	MCS 24
Degradation in dB	0.53	0.52	0.55	0.46	0.65	0.57

References

[1] J. Huschke and M.-A. Phan, “An Overview of the Cellular Broadcasting Technology eMBMS in LTE,” in Next Generation Mobile Broadcasting, pp. 223-252, March 2013.

[2] F. Hartung, U. Horn, J. Huschke, M. Kampmann, T. Lohmar, and M. Lundevall, “Delivery of Broadcast Services in 3G Networks,” *IEEE Transactions on Broadcasting*, vol. 53, no. 1, pp. 188-199, March 2007.

[3] D. Lecompte and F. Gabin, “Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-Advanced: Overview and Rel-11 Enhancements,” *IEEE Communications Magazine*, vol. 50, no. 11, pp. 68-74, Nov. 2012.

[4] J. Kim, S. W. Choi, W.-Y. Shin, Y.-S. Song, and Y.-K. Kim, “Group Communication over LTE: A Radio Access Perspective,” *IEEE Communications Magazine*, vol. 54, no. 4, pp. 16-23, April 2016.

[5] 3GPP TR 36.890 v13.0.0, “Study on Support of single-cell point-to-multipoint transmission in LTE,” July 2015.

[6] T. Stockhammer, I. Bouazizi, F. Gabin, J.M. Guyot, C. Lo, and T. Lohmar, “Enhanced TV Services over 3GPP MBMS,” *Proc. International Broadcasting Convention (IBC)*, Amsterdam, September 2017.

[7] 3GPP TS 23.303 v12.8.0, “Technical Specification Group Services and System Aspects; Proximity-based services (ProSe); Stage 2 (Release 12),” March 2016.

[8] 3GPP TS 23.303 v13.6.0, “Technical Specification Group Services and System Aspects; Proximity-based services (ProSe); Stage 2 (Release 12),” Dec. 2016.

[9] ETSI TS 122 185 v14.3.0, “LTE; Service requirements for V2X services (Release 14),” March 2017.

[10] 3GPP TR 36.888, “Technical Specification Group Radio Access Network; Study on provision of low-cost Machine-Type Communications (MTC) User Equipments (UEs) based on LTE (Release 12)”.

[11] 3GPP TR 45.820 Technical Specification Group GSM/EDGE Radio Access Network; Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT) (Release 13)

[12] 3GPP TR 26.850, “Technical Specification Group Services and System Aspects; MBMS for IoT; (Release 15),”.

[13] 3GPP TS 36.300 v13.5.0, “Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN); overall description; stage 2 (Release 13),” Sept. 2016.

[14] 3GPP TS 36.868 v12.0.0, “Evolved Universal Terrestrial Radio Access (E-UTRA); Study on group communication for E-UTRA; (Release 12),” March 2014.

[15] L. Fay, L. Michael, D. Gomez-Barquero, N. Ammar, and M. W. Caldwell, “An Overview of the ATSC 3.0 Physical Layer Specification,” *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 159-171, March 2016.

[16] I. Eizmendi, *et al*., “DVB-T2, the Second Generation of Terrestrial Digital Video Broadcasting System,” *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 258-271, June 2014.

[17] International Telecommunications Union (ITU), Draft New Report ITU-R M., “Minimum requirements related to technical performance for IMT-2020 radio interface(s)”, Feb. 2017.

[18] International Telecommunications Union (ITU), Draft New Report ITU-R M., “Guidelines for evaluation of radio interface technologies for IMT-2020”, Oct. 2017.

[19] 3GPP TS 22.261 v15.2.0, “Service requirements for the 5G system,” Sept. 2017.

[20] 3GPP TR 38.913 v14.3.0, “Study on scenarios and requirements for next generation access technologies,” June 2017.

[21] 5G-PPP 5G-Xcast project, “Definition of Use Cases, Requirements and KPIs,” Deliverable D2.1 v1.0, October 2017.

[22] International Telecommunications Union (ITU), ITU-R BT.2143-2, “Boundary coverage assessment of digital terrestrial television broadcasting signals”, October 2010.

[23] International Telecommunications Union (ITU), ITU-R M.2083, “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond”, September 2015.

[24] 3GPP TR 45.820 v13.1.0, “Cellular system support for ultra low complexity and low throughput Internet of Things (CIoT),” Nov. 2015.

[25] 3GPP TR 36.888 v12.0.0. “Study on provision of low-cost Machine-Type Communications (MTC) User Equipments (UEs) based on LTE (Release 12),” June 2013.

[26] 3GPP TS 36.213 v14.2.0, “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 14),” March 2017.

[27] N. Loghin, *et al*., “Non-Uniform Constellations for ATSC 3.0," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 197-203, March 2016.

[28] ETSI TR 102 831 v1.2.1, “Implementation guidelines for a second generation digital terrestrial television broadcasting system (DVB-T2),” Aug. 2012.

[29] P. Klenner, J. S. Baek, N. S. Loghin, D. Gomez-Barquero and W. S. Ko, "Physical Layer Time Interleaving for the ATSC 3.0 System," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 253-262, March 2016.

[30] D. Gozalvez, D. Gomez-Barquero, T. Stockhammer and M. Luby, “AL-FEC for Improved Mobile Reception of MPEG-2 DVB-T Transport Streams,” *International Journal of Digital Multimedia Broadcasting*, vol. 2009, pp. 1-10, 2009.

[31] D. Gomez-Barquero, P. F. Gomez, D. Gozalvez, B. Sayadi and L. Roullet, "A Novel Physical Layer Split FEC Scheme for Long Time Interleaving With Fast Zapping Support," *IEEE Transactions on Broadcasting*, vol. 58, no. 2, pp. 269-276, June 2012.

[32] Z. Ding, *et al*, “Application of Non-Orthogonal Multiple Access in LTE and 5G Networks.” *IEEE Communications Magazine*, Feb. 2017.

[33] E. Garro, J. J. Gimenez, S. I. Park and D. Gomez-Barquero, "Layered Division Multiplexing With Multi-Radio-Frequency Channel Technologies," *IEEE Transactions on Broadcasting*, vol. 62, no. 2, pp. 365-374, June 2016.

[34] 3GPP TR 36.859, “Study on Downlink Multiuser Superposition Transmission (MUST) for LTE”, August 2016.

[35] 3GPP TR 38.812, “Study on Non-Orthogonal Multiple Access (NOMA) for NR”, 2017.

[36] S.I. Park, J.Y. Lee, S. Myoung, L. Zhang, Y. Wu, J. Montalban, S. Kwon, B.M. Lim, P. Angueira, H.M. Kim, N. Hur, and J. Kim, “Low Complexity Layered Division for ATSC 3.0.” *IEEE Transactions on Broadcasting*, vol. 62, no. 1, March 2016.

[37] J. J. Gimenez, E. Stare, S. Bergsmark, and D. Gomez-Barquero, “Time Frequency Slicing for Future Digital Terrestrial Broadcasting Networks,” *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 227-238, June 2014.

[38] L. Stadelmeier, D. Schneider, J. Zolner, and J.J. Gimenez, “Channel Bonding for ATSC 3.0”, *IEEE Transactions on Broadcasting*, vol. 62, no. 1, March 2016.

[39] BBC, “Background Information on Inter-Site Distances,” 3GPP TSG WG RAN1, R1-167090, August 2016.

[40] P. Moss, T. Y. Poon, and J. Boyer, “A Simple Model of the UHF Cross-polar Terrestrial Channel for DVB-NGH," White Paper 205, BBC R&D, Sept. 2011.

[41] EBU Technical Report TR026, “Available Options for the Distribution of Broadcast Services,” July 2014 [online].

[42] J. J. Gimenez, E. Stare, S. Bergsmark and D. Gomez-Barquero, "Advanced Network Planning for Time Frequency Slicing (TFS) Toward Enhanced Efficiency of the Next-Generation Terrestrial Broadcast Networks," *IEEE Transactions on Broadcasting*, vol. 61, no. 2, pp. 309-322, June 2015.

[43] R. Brugger and D. Hemingway, "OFDM Receivers. Impact on coverage of inter-symbol interference and FFT window positioning", *EBU Technical Review*, July 2003.

[44] A. Awada, M. Säily and L. Kuru, "Design and performance impact of long cyclic prefixes for eMBMS in LTE networks," *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Doha, 2016.

[45] EBU Technical Report 3348, "Frequency and Network Planning Aspects of DVB-T2," Oct. 2014 [online].

[46] E. Garro, J. J. Gimenez, S. I. Park and D. Gomez-Barquero, "Scattered Pilot Performance and Optimization for ATSC 3.0," *IEEE Transactions on Broadcasting*, vol. 63, no. 1, pp. 282-292, March 2017.

[47] 3GPP, R1-1611609, "Initial acquisition and system information for eMBMS for 100% MBSFN subframe allocation,".

[48] 3GPP, R1-1611493, "Performance results for cell acquisition subframe,".

[49] D. He, K. Shelby, M. Earnshaw, Y. Huang, H. Xu and S. I. Park, "System Discovery and Signaling Transmission Using Bootstrap in ATSC 3.0," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 172-180, March 2016.

[50] L. Zhang, Y. Wu, G. K. Walker, W. Li, K. Salehian and A. Florea, "Improving LTE eMBMS With Extended OFDM Parameters and Layered-Division-Multiplexing," *IEEE Transactions on Broadcasting*, vol. 63, no. 1, pp. 32-47, March 2017.

[51] V. Pauli, I. Viering, C. Buchner, E. Saad, G. Liebl and A. Klein, "Efficient Link-to-System level Modeling for Accurate Simulations of MIMO-OFDM Systems," *Proc. IEEE International Conference on Communications (ICC) 2009*, Dresden, Germany, 2009.

[52] K. Brueninghaus, *et al.*, "Link performance models for system level simulations of broadband radio access systems," *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2005*, Berlin, Germany, 2005.

[53] Motorola, "Simulation Methodology for EUTRA UL: IFDMA and DFT-Spread-OFDMA," 3GPP TSG WG RAN1, R1-051335, November 2005.

[54] EBU Technical Report TR034, "Simulation Parameters for Theoretical LTE eMBMS Network Studies," Dec. 2015.

[55] GSA 4G market and technology, "LTE Broadcast," Jan. 2017.

[56] GSA Evaluating the LTE Broadcast Opportunity, "Innovation Observatory," Nov. 2015 [online].

[57] European Commission RSPG. Strategic roadmap towards 5G for Europe. Opinion on spectrum related aspects for next generation wireless systems (5G). 09 November, 2016 [online].

[58] European Commission. Montenegro Villacieros Belen. JRC Technical Reports. Implications of WRC-15 on spectrum and 5G. 2016 [online].

[59] Ofcom, "Update on 5G spectrum in the UK," Feb. 2017 [online].

[60] 2014/276/EU: Commission Implementing Decision of 2 May 2014 on amending Decision 2008/411/EC on the harmonisation of the 3400 - 3800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community (notified under document C(2014) 2798.

[61] Ofcom, "Improving consumer access to mobile services at 3.6 GHz to 3.8 GHz," July 2017 [online].

[62] EBU Technical Report TR018 v2.0, "Frequency bands allocated to broadcasting," July 2017.

[63] ITU-R Radio Regulations, No. 119-16, Geneva, 15 July 2016.

[64] FCC DA 17-314, “Incentive auction closing and channel reassignment public notice,” April 2017, [online]

[65] 3GPP TR 36.743 v0.1.0, “eMBMS enhancements for LTE Release 14,” May 2016.

[66] ECC DEC (15)01, “ECC Decision of 6 March 2015 on Harmonised technical conditions for mobile/fixed communications networks (MFCN) in the band 694-790 MHz including a paired frequency arrangement (Frequency Division Duplex 2x30 MHz) and an optional unpaired frequency arrangement (Supplemental Downlink),” [online]

[67] ECC Report 239, “Compatibility and sharing studies for BB PPDR systems operating in the 700 MHz range,” Sept. 2015 [online].

[68] ECC Decision (13)03, “The harmonised use of the frequency band 1452-1492 MHz for Mobile/Fixed Communications Networks Supplemental Downlink (MCFN SDL),” Approved on Nov. 2013 and amended on July 2015 [online].

[69] ECC Report 227. Compatibility Studies for Mobile/Fixed Communication Networks (MFCN) Supplemental Downlink (SDL) operating in the 1452-1492 MHz band. Approved January 2015 [online].

[70] ECC Report 202. Out-of-Band emission limits for Mobile/Fixed Communication Networks (MFCN) Supplemental Downlink (SDL) operating in the 1452-1492 MHz band. September 2013 [online].

[71] 3GPP TR 36.895 v13.0.0 (RAN4), “E-UTRA – European 700 supplemental downlink band (738-758 MHz) in E-UTRA,” Jan. 2016.

[72] 3GPPP TR 37.814, “L-band for Supplemental Downlink,”.

[73] Y. Seppo, *et al*. "Coexistence of digital terrestrial television and 4G LTE mobile network utilizing supplemental downlink concept: a real case study,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 5422-5434, 2017.

[74] ITU-R GE06. 2006. Plans for VHF/UHF analogue and digital broadcasting in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz, Geneva 2006 (GE06).

[75] FCC 08-260, “Second report and order and memorandum opinion and order. In the matter of Unlicensed operation in the TV broadcast bands. Additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band,” Sept. 2010 [online].

[76] FCC 10-174, “Second memorandum opinion and order. In the matter of Unlicensed operation in the TV broadcast bands. Additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band,” Nov. 2008 [online].

[77] FCC 12-36, “Third memorandum opinion and order. In the matter of Unlicensed operation in the TV broadcast bands. Additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band,” April 2012 [online]

[78] IDA’s Decision and explanatory memo on the Regulatory framework for TV White Space operations in the VHF/UHF bands on June 16, 2014 [online].

[79] Ofcom Statutory Instruments 2015 No. 2066. Electronic Communications. The Wireless Telegraphy (White Space Devices) (Exemption) Regulations 2015. Came into force on December 31, 2015 [online].

[80] Wise-project measurement report: Airspan Wimax field measurements in Espoo. Internal report. 7.5.2012.

[81] Meld Technology, “Mobile Broadcast White Paper,” Jan. 2014 [online].

[82] ECC CEPT Report 58, “Technical sharing solutions for the shared use of the 2300-2400 MHz band for WBB and PMSE,” 2015 [online].

[83] ECC Report 254, “Operational guidelines for spectrum sharing to support the implementation of the current ECC framework in the 3600-3800 MHz range,” Nov. 2016 [online].

[84] ETSI TS 103 235 v.1.1.1, “System Architecture and High Level Procedures for operation of Licensed Shared Access (LSA) in the 2300 MHz-2400 MHz band,” 2015, [online].

[85] ETSI DTR/RRS-0148. Work Item. Feasibility Study on temporary spectrum access for local high-quality wireless network, [online].

[86] 3GPP TR 32.855, “Study on OAM support for Licensed Shared Access (LSA); (Release 13),” 2015.

[87] FCC 15-47, “Amendment of the Commission’s Rules with Regard to Commercial Operations in the 3550-3650 MHz Band,” GN Docket 12-354, FCC 15-47, Report and Order and Second Notice of Proposed Rulemaking,” April 2015 [online]

[88] FCC 16-55, “Amendment of the Commission’s Rules with Regard to Commercial Operations in the 3550-3650 MHz Band,” GN Docket 12-354, FCC 16-55, Order on Reconsideration and Second Report and Order,” [online]

[89] Title 47, Code of Federal Regulations, Part 96 (2015) [online]

[90] WINNF-TS-0112 v1.1.0, “Requirements for Commercial Operation in the U.S. 3550-3700 MHz Citizens Broadband Radio Service Band,” July 2017 [online]

[91] M. Kyung, “CBRS: New shared spectrum enables flexible indoor and outdoor mobile solutions and business models,” CBRS White Paper, March 2017.

[92] ETSI RRS, DTR/RRS-0148: Feasibility study on temporary spectrum access for local high-quality wireless networks, Early draft 0.0.6, June 2017.

[93] S. Yrjölä, *et al*., “LSA evolution enables local high-quality wireless networks,” *Proc. Winncomm 2017*, San Diego, USA, 2017.

[94] 3GPP TR 36.872, “Small cell enhancements for E-UTRA and E-UTRAN - Physical layer aspects,”.

[95] 3GPP TR 36.843, “Study on LTE device to device proximity services; Radio aspects,”.

[96] LTE-U Technical Report Coexistence Study for LTE-U SDL V1.0 (2015 -02).

[97] 3GPP TS 36.889, “Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum,”.

[98] 3GPP TR 36.790, “LAA/eLAA for the “CBRS” 3.5GHz band in the United States,” .

[99] 3GPP TS 36.360, “LTE-WLAN Aggregation Adaptation Protocol (LWAAP) specification,”.

[100] MulteFire Release 1.0.1, Aug. 2017 [online].

[101] T. Tuukkanen, *et.al*, “Armed Forces' views on Shared Spectrum Access,” *Proc. ICMCIS 2017*.

[102] FCC (2016) 16-55, “The Second Report and Order and Order on Reconsideration finalizes rules for innovative Citizens Broadband Radio Service in the 3.5 GHz Band (3550–3700 MHz).

[103] T. Kokkinen, H. Kokkinen, and S. Yrjölä, “Spectrum broker service for micro-operator and CBRS Priority Access Licenses,” *Proc. EAI International Conference Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM)*, 2017.

[104] 3GPP TS 36.331 v13.3.0, “Evolved universal terrestrial radio access (E-UTRA); radio resource control (RRC); protocol specification (Release 13),” Sept. 2016.

[105] ETSI TS 102 585, “Digital Video Broadcasting (DVB); System Specifications for Satellite services to Handheld devices (SH) below 3 GHz,”

[106] ETSI EN 302 755, “Digital Video Broadcasting (DVB); Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2),”

[107] 3GPP TS 36.211, “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation”.

[108] 3GPP TS 36.212, “Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding”.

[109] ITU-R BT.2215-5, “Measurements of protection ratios and overload thresholds for broadcast TV receivers Report,” July 2015.

[110] G. Faria, J. A. Henriksson, E. Stare and P. Talmola, "DVB-H: Digital Broadcast Services to Handheld Devices," *Proceedings of the IEEE*, vol. 94, no. 1, pp. 194-209, Jan. 2006.

[111] B. Alamanac, *et al*., "Performance Validation of the DVB-SH Standard for Satellite/Terrestrial Hybrid Mobile Broadcasting Networks," *IEEE Transactions on Broadcasting*, vol. 57, no. 4, pp. 802-825, Dec. 2011.

[112] LTE Broadcast Alliance, “LTE Broadcast – Lessons learned from Trials and Early Deployments”, White paper, Nov. 2016 [online].

[113] L. Zhang, *et al*., “Improving LTE eMBMS system spectrum efficiency and service quality using channel bonding, non-orthogonal multiplexing and SFN,” *Proc. IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Nara, Japan, 2016.