Title:

3GPP Enhancements for Television Services: LTE-based 5G Terrestrial Broadcast

Abstract:

The provision of Terrestrial Broadcast services using 3GPP technologies was enabled for the first time in LTE Advanced Pro Release (Rel-) 14, in which the evolved Multimedia Broadcast Multicast Service (eMBMS) technology was enhanced to fulfill a wide set of requirements input by the broadcast industry. During the Enhancements for Television (EnTV) work item in Rel-14 several modifications were realized affecting system architecture, core and radio access. Among others, an interface to grant control to broadcasters to establish audio-visual services, am Application Programming Interface for developers to simplify access to eMBMS procedures, or a transparent delivery mode with native content formats. At the radio layer dedicated carriers with 100% broadcast content allocation were enabled, and also new OFDM numerologies to support larger inter-site distances in Single Frequency Networks (SFN). The most significant change was the so-called receive-only mode which enables devices receiving broadcast content with no need for uplink capabilities, SIM cards or network subscriptions, i.e. free-to-air reception.

In Rel-16 3GPP carried out a study item to evaluate EnTV Rel-14 against the terrestrial broadcast requirements for 5G defined in 3GPP TR 38.913. Two requirements were detected as not met: the ability to support SFN with cell coverage range of up to 100 km, and mobile reception with speeds up to 250 km/h. A Rel-16 Work Item standardized further improvements while taking into account practical considerations such as implementation complexity and performance. The improved system is known as LTE-based 5G Terrestrial Broadcast, and also with the popular name 5G Broadcast.

Keywords:

5G, broadcast, eMBMS, EnTV, digital terrestrial television.

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1. Broadcast Services in 3GPP

The fifth generation of cellular communications systems, popularly known as 5G, has been standardized by 3GPP (3rd Generation Partnership Project), the global standardization forum for cellular communications. 3GPP is formed by seven regional telecommunication standards development organizations (SDOs) as primary members, and a variety of other market representation organizations as associate members. The standardization process in 3GPP is organized in terms of so-called releases, which are published every 15 to 18 months. Each new release consists of about 1.200 different technical specifications. Some of them are only a few pages long, while others extend over hundreds of pages.

The first full set of 5G specifications were standardized in Release 15 (Rel-15). Rel-15 was structured in three phases. A so-called "early drop" was initially approved in December 2017 to accelerate initial availability of 5G specifications for very first deployments. It set out a network configuration which connects the newly introduced air interface known as New Radio (NR) to the so-called Evolved Packet Core (EPC) of a fourth-generation Long Term Evolution (LTE) network. In this network configuration, LTE is used for the control plane (e.g. signaling information and mobility procedures such as handovers) and NR is used for the user (data) plane (i.e. data transmission). In June 2018, the main 5G NR Standalone (SA) version was specified. It defines a new next generation 5G core network and both user and control plane capabilities for NR, so that it can be deployed without any dependency on existing LTE networks. The last drop of Rel-15 was approved mid-2019 to enable the 5G core to inter-work also with an LTE Radio Access Network (RAN). This allows service continuity between NR and LTE, and also exploiting dual connectivity by aggregating NR carriers to LTE, and vice-versa.

Although 5G is commonly associated to the NR air interface [1] (and the new service-enabled 5G core), for 3GPP the label "5G" actually means Rel-15 onwards. This term also applies to LTE with its enhancements in Rel-15. Indeed, 3GPP submitted both LTE and NR as candidate radio interface technologies to the IMT-2020 evaluation process of the International Telecommunications Union (ITU). The framework of standards for International Mobile Telecommunications (IMT) of the ITU spans 3G (IMT-2000), 4G (IMT-Advanced) and 5G (IMT-2020). IMT-2020 defines the minimum requirements [2] and evaluation guidelines [3] related to technical performance for 5G radio interface in three usage scenarios, including enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine type communications (mMTC). For completeness, it should be pointed out that the 3GPP submission includes Rel-15 and Rel-16 (both NR and LTE). The latter was concluded in 2019 and includes a number of enhancements with respect to Rel-15, mostly for URLCC communications.

Regarding broadcast capabilities in 5G, the new NR radio access technology and the 5G core in Rel-15 and Rel-16 only support point-to-point (PTP) unicast transmissions. 3GPP decided to prioritize the work in these areas despite the fact that broadcast was considered by many stakeholders as an integral part of the 5G system from the beginning [4]. Multicast/broadcast transmissions are nowadays considered an essential feature to enable new applications in a number of vertical sectors, such as Automotive, Internet of Things (IoT), Media & Entertainment (M&E) and Public Protection and Disaster Relief (PPDR) [5]. At the time of writing this article in October 2019, there are good prospects that multicast/broadcast enhancements for the new radio and core will be addressed by 3GPP in Rel-17.

On the other side, the LTE technology was originally designed to support broadcast services. eMBMS (evolved Multimedia Broadcast Multicast Services) [6], also known as LTE Broadcast, was introduced in Rel-9 after the initial LTE standard in Rel-8. A major step forward with respect to broadcast capabilities came with Rel-14 as a result of a study entitled "Enhancement for TV service (EnTV)". This study got European broadcasters involved in 3GPP which let to submitting their requirements [7], including the obligation of public service broadcasters to offer linear TV and radio programs free-to-air (FTA).

After the work in Rel-14, 3GPP carried out a study item in Rel-16 to perform a gap-analysis and evaluate eMBMS Rel-14 against the terrestrial broadcast requirements for 5G NR defined in [8]. Two requirements were detected as not met, and a follow-up Rel-16 Work Item standardized further improvements, while taking into account practical considerations such as implementation complexity and performance. The improved eMBMS system as a result of this activity is known as LTE-based 5G Terrestrial Broadcast, since it's Rel-16 (5G) but LTE-based.

It should be pointed out that the IMT-2020 submission template [3] includes a section on "Unicast, multicast and broadcast," where it should be described whether the radio interface technology enables: (i) broadcast capabilities, (ii) multicast capabilities, (iii) unicast capabilities; using both dedicated carriers and/or shared carriers. It is also requested to describe how all three capabilities can exist simultaneously. The 3GPP submission to the IMT-2020 evaluation process will, in principle, include eMBMS Rel-16 as 5G radio access broadcast technology.

This article provides an overview of the LTE-based 5G Broadcast eMBMS technology up to Rel-16. The rest of the article is structured as follows. Section 2 reviews the requirements for terrestrial broadcast in 3GPP. Section 3 describes the evolution of the eMBMS technology in 3GPP until Rel-16. Section 4 covers eMBMS architecture and core network. Section 5 is devoted to the eMBMS Radio Access Network. Section 6 provides a literature review about performance evaluation results of eMBMS for terrestrial broadcast. The article is concluded with an outlook in Section 7.

2. 3GPP Requirements for Terrestrial Broadcast

3GPP Rel-14 EnTV Requirements

Previous attempts to integrate a mobile broadcast receiver in portable and mobile 3GPP devices such as smartphones and tablets have failed (e.g., DVB-H, DVB-SH, Media FLO) [9]. The EnTV study opened the opportunity for broadcasters to offer all their services – both linear and nonlinear – to 3GPP devices, enabling broadcast capabilities within the 3GPP system itself.

Up to Rel-13, eMBMS was limited by some constraints that let it appear very unattractive for broadcasters. A maximum of 60% of a radio carrier could be allocated to eMBMS. The rest had to stay reserved for unicast connections. This means that eMBMS in this variant could only be instantiated in traditional mobile network setup and run by a traditional mobile operator. This came along with the fact that eMBMS could only be implemented for transmitter inter-site distances that can be found in typical 3G/4G mobile networks, i.e., less than a few kilometers at maximum.

The engagement of broadcasters in 3GPP was led by the Strategic Programme on Distribution of the European Broadcasting Union (EBU) which coordinated all activities. EBU represents a union of currently 116 public service media companies from 56 countries [10] with a potential audience reach of more than one billion people. EBU's remit comes with very particular requirements which need to be met by its members. Broadcasting companies such as NHK from Japan supported the EBU initiative. Only recently there is interest in broadcast features rising in China as well.

Linear TV services can be accessed on portable and mobile devices by means of live streams. However, this quickly consumes the data volume of typical mobile data plans. In essence, only few hours of linear TV consumption per month are possible unless users are prepared to pay more. For most public service media companies this poses a severe issue as they have to offer, at least, their linear services free-to-air. This means that apart from the monthly license fee and the expenses for receiving equipment not further costs must be borne, in particular no recurring costs. This gave rise to one of most important requirements EBU submitted to 3GPP, i.e. the possibility to deliver linear TV services free-to-air. This means in other words that the device does not need to be connected to a base station. Rather, it behaves as a broadcast receiver. This feature is sometimes also addressed as receive-only mode or SIM-free reception.

Broadcasters have operated their own networks to distribute linear radio and TV services for many decades. Even though most public service broadcasters have given up network operation, distribution of linear services over dedicated downlink-only broadcast networks is, and seems to remain, a fundamental pillar of the global broadcasting industry. This is important because linear services are still strongly requested by users, especially for mass events, such as news, sports or Saturday evening entertainment. Having control over the distribution also allows direct access to consumers. Two main issues were identified to implement the possibility of network operation in the 3GPP system. Firstly, eMBMS until Rel-14kept 40% of a carrier for unicast procedures. Consequently, only a mobile network operator can offer this type of eMBMS. In order to allow other operators, for example broadcast network operators, to provide linear TV free-to-air this limitation had to be removed. This led to requesting the possibility of a 100% eMBMS carrier. Secondly, broadcast network operators should be in a position to re-use their existing network infrastructure. In contrast to typical mobile networks the inter-site distance between adjacent transmitter is significantly larger in broadcast networks. Furthermore, to use spectrum efficiently single frequency networks are typically used. Both elements suggested to request an extension of the OFDM cyclic prefixes used in eMBMS. This requirement is often referred to as the possibility to use so-called high-power-high-tower (HPHT) networks. HPHT is also a key feature to allow for large area broadcast coverage.

These provisions enable what is called standalone downlink-only (SDO) networks. The option to set aside a network for a particular purpose was considered important to reach all consumers irrespective with which mobile operator they have a contract. In order to do so two scenarios were discussed. If a public service broadcaster wants to provide linear free-to-air TV services for all mobile costumers, it could make contract with all mobile operators to transmit corresponding signals over their networks. However, this would constitute a significant waste of resources and money as all mobile operators would need to cover a given territory leading to multiple coverages. The second scenario was the dedicated standalone network which means to roll-out a single infrastructure to serve everyone. Obviously, sharing infrastructure between different operators would be key to enable that. Consequently, infrastructure sharing was high on the list of broadcaster’s requirements.

Figure 1 sketches the high-level requirements submitted by European broadcasters.

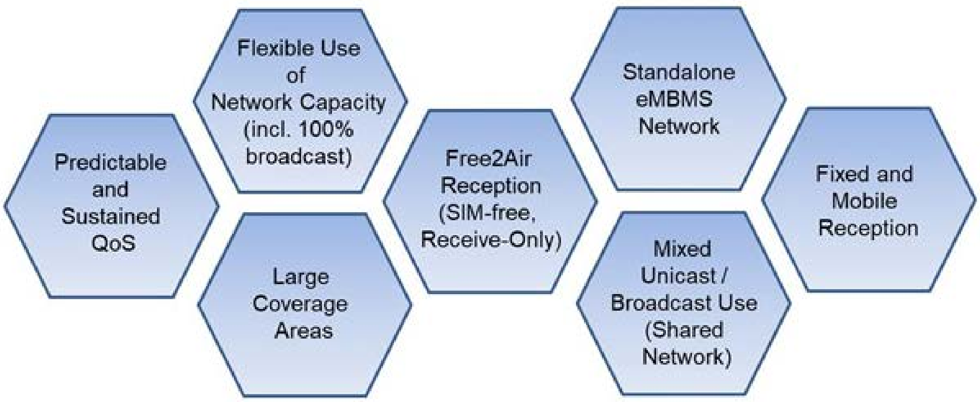


Figure 1: *High-level requirements for the distribution of broadcast content and services of 3GPP EnTV in Rel-14.*

3GPP Rel-16 5G Requirements

5G requirements were defined in 3GPP in TS 22.261 [10] and in TR 38.913 [8]. In section 9.1 of the latter TR requirements for MBMS under NR have been collated. The EBU participated in this activity in order to make sure that multicast and broadcast features for NR to be specified at a later point in time would seamlessly link to the work carried out in EnTV, closing existing gaps and introducing new functionalities. This means that naturally existing audio-visual (AV) services should be supported such as linear audio and video programmes, download and streaming of AV content and AV based group communication. Furthermore, new types of services in various distinct market sectors, i.e. the so-called verticals, should also be enabled. Emphasis was put on the possibility to dynamically switch between unicast, multicast and broadcast modes in order to respond to changing demands for example as a consequence of varying user distributions and concurrent services requests. Transmitter inter-site distances even beyond should be envisaged to cater for very large coverage areas as well as dedicated modes to support mobile MBMS services up to 250 km/h speeds.

3. Evolution of eMBMS Capabilities

eMBMS introduced new point-to-multipoint radio bearers and multicast support in the core network with small changes to the existing radio and core network protocols of LTE [6]. New physical, transport and logic channels were defined, as well as three new logical entities in the core network architecture. The implementation of eMBMS requires changes from the physical layer up to the core network. These concern the control and user planes which are conveyed over a series of radio bearers, logical channels, transport channels and physical channels which differ from the regular channels used for unicast traffic.

Since its introduction in Rel-9, eMBMS has evolved in all subsequent releases going through a very significant set of enhancements, with major changes and improvements to the core network architecture and the RAN. 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. It should be noted that these improvements are not backwards compatible with previous releases, meaning that pre-Rel-14 UEs cannot receive any terrestrial broadcast service from cells operating with these improvements, and hence they are only suitable for new Rel-14 deployments and new devices.

Figure 2 depicts the evolution of eMBMS in LTE. The improvements can be generally classified around two areas:

- Generic delivery efficiency enhancements using PTM as an internal and dynamic delivery optimization tool (out of the scope of this article – a brief description of the improvements from Rel-10 to Rel-14 is presented next).
- Enhancements for the delivery of TV services to deploy standalone eMBMS broadcast networks (focus of this article – the main enhancements in Rel-14 and Rel-16 are detailed in this section).

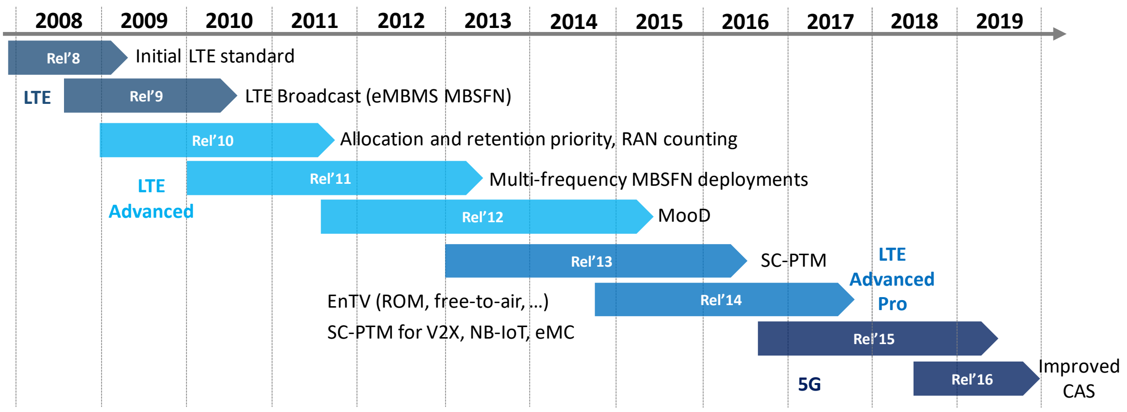


Figure 2: *LTE-based eMBMS Evolution in 3GPP. Acronyms: MBSFN (MBMS over Single Frequency Network), MooD (MBMS Operation on Demand), SC-PTM (Single Cell – Point to Multipoint), ROM (Receive-Only Mode), V2X (Vehicular to Anything), NB-IoT (NarrowBand Internet of Things), eMC (enhanced Mission Critical communications).*

eMBMS Rel-9 was largely based on the original MBMS technology standardized for 3G in Rel-6 [12], which was initially conceived as an add-on mobile TV service in a large pre-planned area with a rather static configuration. In order to increase the resource allocation flexibility for PTM transmissions, eMBMS was enhanced with MooD (MBMS operation on Demand) [13] in Rel-12 and SC-PTM (Single-Cell PTM) [14] in Rel-13. MooD enables automatic and seamless MBMS service activation and deactivation based on the UEs' service consumption reporting that was introduced in Rel-10. 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 for broadcast a different and dedicated physical channel, the physical multicast channel ((P)MCH). This allows a very flexible and dynamic radio resource allocation for broadcast transmissions, equivalent to unicast, with a reduced end-to-end latency. SC-PTM was included for vehicular communications and machine-type communications in Rel-14. Other important improvement was the introduction of service acquisition and continuity in multi-frequency deployments where the MBMS service is provided via more than one frequency in Rel-11 [15].

Release 14 – Enhancements for TV Services (EnTV)

The key enhancements to the eMBMS system architecture introduced in EnTV are [16], [17]:

- A **Receive-Only device Mode (ROM)** to enable free-to-air content broadcast that can be received by all devices, including devices without uplink capabilities, SIM cards or 3GPP network subscriptions. One specific application of ROM is to enable **free-to-air** content broadcast over eMBMS. Subscribers with a broadband connection, either mobile with a SIM card or fixed, can nevertheless access interactive services in parallel.
- A new (broadcasting application programming) standardized **xMB interface** to simplify the access to eMBMS system functionalities of content providers and broadcasters to establish audio-visual services [18]. The xMB interface decouples eMBMS transport from content and service layers, i.e. control and user plane separation.
- A new open standardized **Application Programming Interface (MBMS-API)** for developers of web and user applications to simplify access to eMBMS procedures in the User Equipment.
- A **transparent delivery mode** (transport-only/pass-through) to use the eMBMS network as content delivery platform that allows reuse of broadcast services without transcoding thereby ensuring backward compatibility and minimal effort to migrate from legacy systems. It allows for example the use of MPEG-2 Transport Stream (TS) over IP (Internet Protocol). This mode was added to not limit the supported TV formats to the standardized 3GPP media layer services.

The key enhancements to the eMBMS Radio Access Network introduced in EnTV are:

- **Dedicated carriers** with up to 100% broadcast content allocation without any resources allocated to unicast and self-contained system information and synchronization signals.
- Support for larger inter-site distances in SFN (Single Frequency Networks) with a **new OFDM numerologies**. For example, a 200 µs OFDM cyclic prefix (CP) was designed to cover 15km ISD with 1.25 kHz subcarrier spacing (SCS). An intermediate numerology with 33 µs CP was also added.
- **Shared broadcast networks** where different operators can aggregate their eMBMS radio access networks to create a common distribution platform avoiding the transmission of the same broadcast content over several networks.
- **New subframe type** without unicast control region to reduce the signaling overhead in downlink-only eMBMS transmissions.

Release 16 – LTE-based 5G Terrestrial Broadcast

With Release 14 EnTV standardized, 3GPP initiated a study item for Release 16 entitled 'Study on LTE-based 5G Terrestrial Broadcast' to check that the solution actually meets the requirements originally input. Several limitations where identified as captured in TR 36.776. In particular, the standard would need improvement to support SFN large area coverage for stations with a cell radii of 100 km, and to support mobility up to 250 km/h. Specification work was started in relevant RAN working groups to specify the required changes. At the time of publishing this chapter, a longer CP of 300 µs with a core symbol duration of 2.7 ms for large area roof-top reception; a new numerology with 100 µs CP and 400 µs core symbol duration for improved mobility are adopted. In addition, the numerology mismatch of the cell acquisition subframe (CAS) was extensively analyzed together with the appropriate methodologies to evaluate it. The proposed improvements consider the repetition and combining of PBCH instances or the increase of aggregation levels for PDCCH.

In addition, for roof-top reception, several studies showed the need of implementing frequency interleaving and new signals for phase tracking.

4. eMBMS Core Network and Architecture

Core Network Architecture

Figure 3 shows the network architecture of eMBMS, with three specific logical entities: the BM-SC (Broadcast/Multicast Service Center), the eMBMS-GW (Gateway) and the MCE (Multi-cell/multicast Coordination Entity).

The BM-SC is the entry point for content into the Evolved Packet Core (EPC). It plays the role of traffic shaper and is responsible for, among other things, service announcement, configuration of transmission and user authentication and encryption. It is also in charge of the synchronization of the transmitted data among LTE evolved base stations (eNode Bs, or eNBs) for MBSFN. The protocol SYNC is used to associate a specific header to IP packets, providing time stamps and session information [6].

The eMBMS gateway is located between the BMSC and all eNBs, and it distributes the eMBMS data to base stations using IP multicast and generates session control signaling for the mobility management entity (user plane interface M1). When the BM-SC initiates a session arrives, the eMBMS gateway allocates an IP multicast address to which the eNBs should join to receive the data. The gateway is also responsible for session announcement and session control signaling (start/stop) towards the RAN via the control plane interface M3.

The MCE is responsible for coordinating the usage of MBSFN transmission within the same MBSFN area. It allocates radio resources in time and frequency for eMBMS and decides the configuration of the radio transmission. The MCE can be centralized into a single logical entity or distributed and implemented in all eNBs.

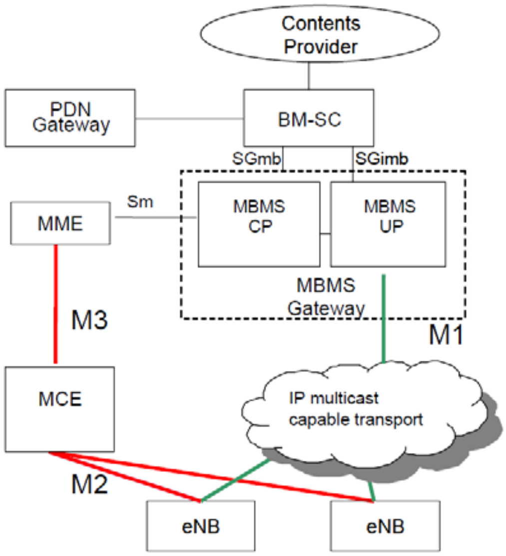


Figure 3: eMBMS architecture. The three logical elements of eMBMS are highlighted. The MCE can also be implemented in a distributed manner in all eNBs.

eMBMS EnTV Architecture

Figure 4 shows a simplified eMBMS architecture for TV services with the new eMBMS application programming interface (MBMS-API) that has been introduced from the MBMS client to the content receiver application and the xMB interface from the content provider to the BM-SC. It should be pointed out that MBMS is split into the MBMS bearer service and the MBMS user service, in such a way that it is possible to integrate PTP and PTM radio bearers in a transparent way to the MBMS service layer. Thus, it is possible to delivery an MBMS service with unicast point to point transmissions.

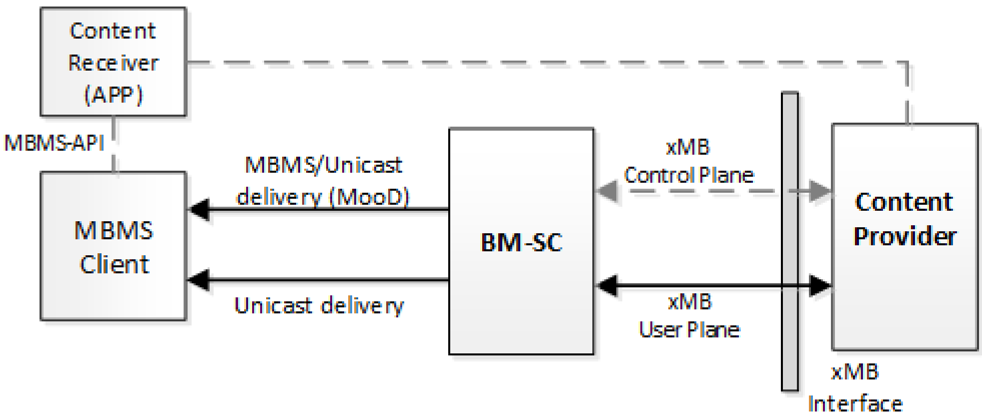


Figure 4: *Simplified architecture for TV services over 3GPP eMBMS Rel-14.*

The MBMS-API exists in the UE from the eMBMS client to the content receiver application and is fed through xMB with relevant information to expose services to applications. This does not preclude typical mobile applications and Over-The-Top (OTT) service approaches, in which the content provider establishes a direct connection apart from the eMBMS broadcast distribution (e.g., for service configuration and updates). Furthermore, to simplify access to the service by third party applications, an MBMS URL scheme has been defined to serve as the entry point to trigger reception of an MBMS service.

The xMB reference point is defined between the content provider and the BM-SC, and it is splitted into user- and control-plane procedures (xMB-U and xMB-C, respectively). The xMB reference point provides the ability for the content provider to:

- authenticate and authorize BM-SC(s).
- create, modify, and terminate (a) service(s).
- create, modify, and terminate (a) session(s).
- query information about the parameters of services/sessions.
- deliver content to/via the BM-SC(s).

The BM-SC can also retrieve content from the content provider using this interface, and to send notifications to the content provider about the status of an eMBMS user's service usage.

The introduction of a new MBMS transparent delivery mode (in addition to download, streaming and group communication) permits the delivery of IP-based service where the media codecs and application protocols are defined outside the MBMS system. A transport-only mode forwards the data and TV content across the network for consumption at the receiver by third party applications. The introduction of this new feature makes it possible to e.g send MPEG-2 Transport Stream (TS) as per those currently in use by other broadcast platforms, that are consumed by a generic MPEG-2 TS tuner. A service announcement channel (SACH) is defined in this case to assist the UE in finding the available MBMS user services on the radio interface.

A further essential feature introduced is the Receive-only Mode (ROM). ROM is a UE configuration option that allows reception of eMBMS broadcast services without the need to access and register with the operator offering such service. To do this a specific Temporary Mobile Group Identity (TMGI) is used in which the Mobile Country code(MCC) and Mobile Network Code (MNC) are assigned by ITU-T to MCC = 901 and MNC = 56, which are used universally for ROM services.

5. eMBMS Radio Access Network

The data transmission in regular LTE subframes is organized by means of a three-dimensional mapping in space, time and frequency. Regarding space, multiple antenna ports are defined at the eNB with a different Reference Signal (RS) pattern so that the UE can equalize the channel. In time, the transmission is organized in frames of 10 ms divided in ten subframes of 1 ms, consisting of two slots of 0.5 ms. In the frequency domain, a Resource Block (RB) comprises a group of contiguous subcarriers (Resource Elements, RE) to a total of 180 kHz. Supported carrier bandwidth are 1.4, 3, 5, 10, 15, and 20 MHz. Frequency-division duplex (FDD), time-division duplex (TDD), and combined FDD/TDD are supported to allow for operation in paired as well as unpaired spectrum allocation.

For eMBMS, only FDD multiplexing is supported, and functionalities such as MIMO or Carrier Aggregation are not supported. Moreover, MBMS carriers (or cells) can be configured into different ways to allocate broadcast data. In general, carriers multiplex in time different types of subframes containing control and user plane data. Specific subframes able to be configured for Single Frequency Network (SFN) operation are known as MBSFN (Multicast Broadcast SFN) subframes. Regular LTE subframes are known as non-MBSFN.

LTE Rel-14/16 includes three different types of MBMS cells:

- MBMS/unicast-mixed cells perform both MBMS (up to 60% of cell capacity) and unicast transmissions and are supported in LTE since Rel-9. Synchronization signals, control channel and paging is scheduled as per regular LTE subframes.
- FeMBMS/unicast-mixed cells are those in which subframes #4 or #9 or both are configured as MBSFN subframes or when subframes do not contain unicast control region. In order to provide unicast, a primary cell is required. Camping of UEs not enabled for this mode is prevented by means of system information. Paging is not supported and may come from a different cell. With this mode, up to 80% of the cell can be configured for broadcast data.
- MBMS-dedicated cells are those cells performing only MBMS transmissions (100% capacity). UEs not supporting this mode are not allowed to camp on these cells. Paging and unicast traffic are not supported in such case.

MBSFN Subframes

A subframe type called MBSFN subframe is defined with a different structure from the unicast (non-MBSFN) subframe to convey the PMCH (Physical Multicast Channel). MBSFN subframes permit configuring OFDM parameters for multi-cell transmissions in single frequency networks. In this case, the cyclic prefix (CP) is extended to cover the difference in the propagation delays so that at the UE the transmission appears as a single large cell, see Fig. 5.

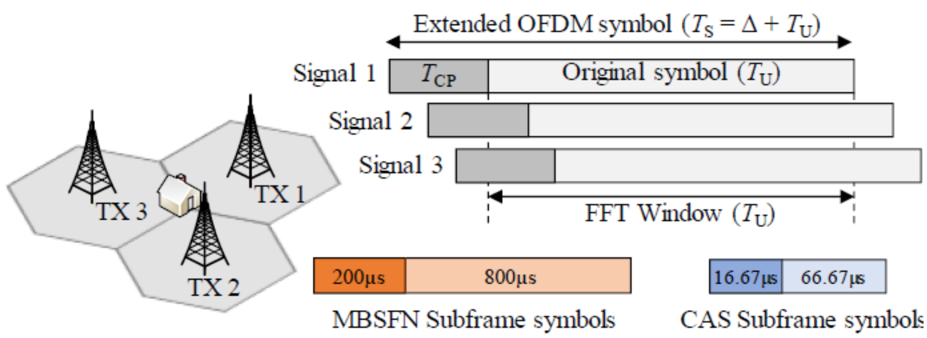


Figure 5: *Single Frequency Network with 3 transmitters. Reception of contributions and role of the cyclic prefix. MBSFN subframes are designed to provide wide area coverage. CAS subframes with legacy OFDM numerology may suffer from a certain degree of interference.*

In addition to the 15 kHz subcarrier spacing with an extended CP of 16.6 µs, MBSFN subframes also support 7.5 kHz with a CP of 33.3 µs and 1.25 kHz with a CP of 200 µs. Note that in order to limit the relative overhead imposed by this extended long CP, the OFDM useful symbol duration is extended accordingly and therefore, capacity remains the similar. On the other hand, narrowing subcarrier spacing makes the system less resilient to Doppler effect and the maximum tolerable receiver speed is reduced accordingly. Table 1 presents an overview of the all the possible OFDM numerologies.

Each MBSFN subframe is divided into a non-MBSFN region and an MBSFN region. For subframes using 15 kHz, the non-MBSFN region spans the first one or two OFDM symbols in an MBSFN subframe with a length depending on the number of cell-specific antenna ports. For subframes with 7.5 kHz or 1.25 kHz the non-MBSFN region is zero.

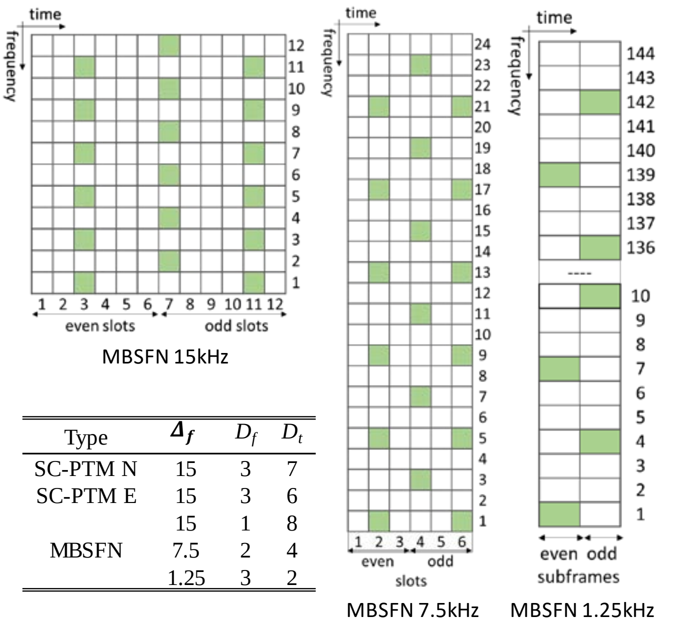
Dedicated reference signals (RS) are defined for MBSFN subframes. MBSFN RS consist of known reference symbols to assist channel estimation and equalization. The MBSFN RS are dense in the frequency domain in order to cope with the higher frequency selectivity caused by delay spread in SFNs, which involve a large capacity overhead. These reference signals are mapped to antenna port 4 what means that only SISO transmissions are possible for MBSFN and they are only defined for extended CP. The values of the MBSFN RS depend on the MBSFN Area ID and all cells within the same MBSFN area transmit the same MBSFN RS at the same time-frequency positions.

TABLE I. OFDM NUMEROLOGY OPTIONS FOR LTE EMBMS RELEASE 14

Type	Δ_f (kHz)	SC_{RB}	OFDM symbols per SF	T_{CP} (μs)	T_U (μs)	ISD (km)
Non MBSFN	15	12	14	4.7/5.1	66.7	--
MBSFN	15	12	12	16.7	66.7	5
	7.5	24	6	33.3	133.3	10
	1.25	144	1	200	800	60

Note that a Resource Block (RB) in LTE is 180 kHz wide in frequency and 1 slot long in time. SCRB=Subcarriers per Resource Block, SF=Subframe, T_{CP}=CP duration, T_U=useful OFDM symbol duration, ISD =SFN Inter-Site Distance.

With respect to multipath or echoes – either artificial or natural – the frequency spacing between reference signals determines the length of delay up to which the channel may be correctly equalized when using time-frequency interpolation. Delays up to the duration of the equalization interval (EI) may be tolerated as shown in Figure 6.



Type	Δ_f	D_f	D_t
SC-PTM N	15	3	7
SC-PTM E	15	3	6
MBSFN	15	1	8
	7.5	2	4
	1.25	3	2

Fig. 6. Reference signals for MBSFN subframes and unicast subframes with different OFDM numerologies.

Non-MBSFN Subframes

Non-MBSFN subframes contain system information and synchronization signals which are transmitted with regular LTE subframes. In MBMS-dedicated cells, these subframes are also known as Cell Acquisition Subframes (CAS). The CAS is transmitted once every 40 subframes and is formed by the following physical channels and synchronization signals: PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal) are used for time and frequency synchronization. The signals are those specified for unicast, therefore also depend on a cell ID (physical cell identity) which identifies the eNB. These signals are transmitted in slot #0.

Note that in MBMS/unicast-mixed or FeMBMS/unicast-mixed cells, PSS/SSS signals are also allocated in slot #10 to obtain frame timing. CS-RS (Cell-Specific Reference Signals) provide amplitude and phase reference for channel estimation. The complex values of the reference symbol signals and the subcarrier mapping offset depend on the cell ID. The standard does not specify any particular value for SFN operation and therefore the correct performance when equal cell IDs are used cannot be guaranteed. PBCH (Physical Broadcast Channel) contains the MIB (Master Information Block). PCFICH (Physical Control Format Indicator Channel) indicates the number of OFDM symbols used for control in the subframe. PDCCH (Physical Downlink Control Channel) contains the DCI (Downlink Control Information). PHICH (Physical Hybrid ARQ Indicator Channel) carries the HARQ ACK/NACK from eNB, which is not used in MBMS-dedicated cells and therefore the corresponding REs are empty. PDSCH (Physical Downlink Shared Channel) transmits SIBs (System information blocks).

RAN Protocols and System Information

Different RAN protocols are involved in eMBMS transmission. On the control plane, RRC handles signaling related to MBSFN transmission conveyed in the BCCH (Broadcast Control Channel) and MCCH (Multicast Control Channel) logical channels.

On the user plane, the Packet Data Convergence Protocol (PDCP) is not used for eMBMS, and at Radio Link Control (RLC) level the Unacknowledged Mode (UM) with no retransmissions is used. At the Medium Access Control (MAC) layer, the MTCH (Multicast Traffic Channel) transmits broadcast data from the network to the UE. The relevant downlink transport channels are the Broadcast Channel (BCH), which transports part of the system information; the Downlink Shared Channel (DL-SCH), used to transport remaining parts of the system information; and the Paging Channel (PCH), which transports paging information to UEs and informs them about updates of the System Information (SI). Note that in dedicated MBMS cells, the uplink is not required to acquire and discover service information and the actual payload.

SI is transmitted to assist the acquisition of the actual data. The Master Information Block (MIB) contains the most essential parameters related to the transmit signal. A number of System Information Blocks (SIBs) carries other SI messages and relevant parameters.

The MIB is acquired via blind decoding with two DCI (Downlink Control Indicator) formats being monitored: DCI format 1A to discover SIBs and DCI format 1C to discover MCCH (Multicast Control Channel). Two RNTI (Radio Network Temporary Identifier): SI-RNTI and M-RNTI are used, respectively. The MIB is mapped to the BCCH, transmitted in the BCH and latter mapped to the PBCH in non-MBSFN subframes. SIBs are generally carried by DL-SCH and mapped to the PDSCH in non-MBSFN subframes.

In regular MBMS, SIB1 and SIB2 are used which contain additional common parameters relevant for unicast and eMBMS transmissions. In FeMBMS/Unicast-mixed cells SIB1-MBMS and SIB2 are used. Only on MBMS-dedicated cells, specific MIB-MBMS and the SIB1-MBMS are scheduled once every 4 CAS with the same MIB-MBMS transmitted in four consecutive CAS to increase detection probability.

SIB2 informs the UE on the subframes reserved for MBSFN. Additionally, SIB13 informs about the subframes that carry MCCH of each MBSFN area. UEs capable of MBMS service continuity can use SIB15 to disclose the frequency of given services in adjacent cells.

The scheduling of MBMS services data is performed by the MCCH in terms of subframe allocation. The MCCH provides control information of one or several MTCHs, which carry the actual payload. Both MTCH and MCCH channels can be mapped into the MCH and the PMCH. Only four MCS (2, 7, 9 and 13) values can be used in the subframe carrying MCCH while with subframes transporting MBMS data, all MCS values are eligible including QPSK, 16-QAM, 64-QAM or 256-QAM.

6. eMBMS Performance Evaluation Literature

This section provides a literature review about performance evaluation results of eMBMS for terrestrial broadcast.

It should be pointed out that FeMBMS cannot be fairly compared with digital terrestrial broadcast technologies, such as DVB-T2 (Digital Video Broadcast – Terrestrial 2nd Generation) [19] or ATSC 3.0 (Advanced Television Systems Committee - Third Generation) [20], because those technologies have been highly optimized for fixed rooftop reception. FeMBMS is inseparably linked to LTE as its reference technology. As such, FeMBMS is meant to target portable and mobile 3GPP devices in first place. As an illustrative example, journal paper [21] provides a detailed performance analysis of the physical layer of (eMBMS) and (ATSC 3.0) using link-level simulations. It is observed that ATSC 3.0 outperforms eMBMS in terms of spectral efficiency, peak data rate and mobility, among others, due to the use of long LDPC codewords, non-uniform constellations and longer time interleaving at the physical layer.

Technical report [22] provides simulation results on the spectral efficiency in an Additive White Gaussian Noise (AWGN) channel as a function of the Signal-to-Noise Ratio (SNR), and spectral efficiency as a function of the inter-site distance for different scenarios and assumptions.

Journal paper [23] presents field trials results of eMBMS in a terrestrial broadcast SFN. The paper compares the measurement data against simulation models for field strength and path loss of each transmitter, eMBMS useful field strength and received power, and Signal-to-Interference plus Noise Ratio (SINR), achieving good alignment. Using the calibrated simulation models, it is shown that the coverage can be improved increasing the OFDM CP duration from 33.33 to 66.67 µs.

The issue of the misalignment of the OFDM numerologies between MBSFN and CAS subframes have been analyzed in [24], [25] and [26]. Conference paper [24] presents SFN coverage simulation results in synthetic scenarios with hexagonal grids and realistic scenarios, and shows that coverage may become limited by the CAS in locations where the MBSFN subframes could potentially be received. Conference paper [25] presents SFN coverage simulation results using ray-tracing path loss models for FeMBMS in an existing DVB-T2 terrestrial broadcast network. The paper shows the contrast of achievable SINR levels between the data and the signaling (CAS). Although the difference in achievable SINR levels is relatively small, the CAS can limit the coverage area significantly. Conference paper [26] evaluates the performance of the FeMBMS dedicated broadcast transmission mode based on a field measurement campaign focusing on the reception performance.

Deliverable [27] evaluates the performance of eMBMS LTE-Advanced Pro as per 3GPP Rel-14 via extensive link level, system level and coverage simulations. The deliverable also identifies technical limitations of the LTE-Advanced-Pro Broadcast RAN in terms of the air interface, radio access technology protocols and spectrum in order to outline potential technologies, procedures and areas of research to overcome such limitations in 5G NR.

7. Outlook

3GPP Rel-14 EnTV represents a major milestone for terrestrial broadcasting in its need to reach portable and mobile devives. The eMBMS technology was enhanced into FeMBMS (Further evolved Multimedia Broadcast Multicast Service) to implement a full broadcast television stack in LTE mobile networks, including free-to-air receive-only services characteristic of public service broadcasting and the deployment of dedicated downlink-only eMBMS networks. Several field trials of Rel-14 FeMBMS technology have taken place worldwide (e.g., Germany, Italy, China and Brazil). Rel-16 work will further improve some features, such as new OFDM numerologies and improved performance of the control access signaling. The joint MBMS characteristics of Rel-14 and Rel-16 will be labeled "LTE based 5G Broadcast".

The question if and to what extent broadcast content and services will be distributed over FeMBMS networks in the future is very difficult to answer today [28], [29]. Although FeMBMS is sometimes addressed as a potential replacement for existing DTT technologies [30], it should be taken noted that FeMBMS has been developed for a different purpose than digital terrestrial television standards. Whereas e.g., DVB-T2 is highly optimized for the distribution of linear TV services for fixed rooftop reception, FeMBMS is meant to reach portable and mobile devices and carries the LTE legacy.

On the other side, 3GPP is standardizing since Rel-15 5G New Radio (NR) and 5G Core (5GC) specifications, with a new and more efficient and flexible radio access layer and core system architecture, but without multicast and broadcast support in Rel-15 and Rel-16. In this sense, there is potential for an improved MBMS system based on 5G NR and 5G that could also solve a number of limitations and inefficiencies of the LTE-based FeMBMS technology [31], [32], [33]. 3GPP may introduce multicast and broadcast support in 5G NR and 5GC in coming Releases. However, Rel-17 will not address terrestrial broadcast requirements.

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