♦ Evolved Multimedia Broadcast Multicast Service in LTE: An Assessment of System Performance Under Realistic Radio Network Engineering Conditions

Alistair Urie, Ashok N. Rudrapatna, Chandrasekharan Raman, and Jean-Marc Hanriot

With the explosive and sustained growth of data usage on both 3G and 4G mobile broadband wireless networks, new techniques need to be found to deliver data to end users efficiently. One of the key drivers of that data demand is video. Evolved Multimedia Broadcast Multicast Service (eMBMS) is one technique in Long Term Evolution (LTE) that provides a broadcast bearer to deliver video content and file delivery to an unlimited number of users. This bearer makes use of multiple cell sites to build a "single frequency network" (SFN) zone with identical downlink transmission over part of the LTE Orthogonal Frequency Division Multiplexing (OFDM) waveform. The resulting signal is combined at the user equipment's antenna in such a way that what is normally a neighboring cell site contributing interference becomes the source of a useful signal, thus improving the overall information signal to interference ratio, as well as spectral efficiency. In this paper, eMBMS technology and architecture are presented along with estimates of achieved performance and the impact on radio network engineering. We conclude that while eMBMS may not be an efficient solution to offer nationwide contiguous services throughout a mobile network, it may be efficiently used across an entire metropolitan area and the surrounding "capacity limited" rural areas when using a low radio band such as 700 MHz or 800 MHz, offering an impressive spectral efficiency of 1.5 b/s/Hz. © 2013 Alcatel-Lucent.

Introduction

Long Term Evolution (LTE), the fourth generation (4G) wireless technology being adopted by most of the world's mobile operators, provides for high capacity and is designed to support a wide variety of services and applications using both "unicast bearers," wherein each user is assigned specific uplink and downlink radio access resources, and "broadcast bearers," wherein multiple users receive the same content over shared downlink resources.

This paper addresses the mechanism used by the LTE system to support broadcast bearers using eMBMS. We describe the Evolved Multimedia Broadcast Multicast Service (eMBMS) network architecture, along with the types of services it can be used for, and follow with descriptions of eMBMS

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Panel 1. Abbreviations, Acronyms, and Terms

3G—Third generation
3GPP—3rd Generation Partnership Project
4G—Fourth generation
BCMCS—Broadcast/Multicast Service
BMSC—Broadcast Multicast Service Center
BLER—Block error rate
BS—Base station
CDMA—Code Division Multiple Access
CP—Cyclic prefix
DAB—Digital Audio Broadcast
DU—Dense urban
DVB—Digital Video Broadcast
DVB-H—DVB–Handheld
DVB-T—DVB for Terrestrial Networks
eMBMS—Evolved MBMS
eNB—Evolved NodeB
EPC—Enhanced packet core
FDD—Frequency division duplexing
FEC—Forward error correction
FFT—Fast Fourier transform
FLUTE—File Delivery over Unidirectional Transport
IETF—Internet Engineering Task Force
IP—Internet Protocol
ISD—Inter site distance
ISI—Inter-symbol interference
LTE—Long Term Evolution
MBMS—Multimedia Broadcast Multicast Service
MBMS-GW—MBMS gateway
MBSFN—Multicast Broadcast Single Frequency Network
MCCH—Multicast control channel
MCE—Multi-cell/multicast coordination entity
MCS—Modulation and coding scheme
MME—Mobility management entity
NE—Network element
NSI—Non-SFN interference
OFDM—Orthogonal Frequency Division Multiplexing
PTT—Push-to-talk
RAN—Radio access network
RFC—Request for comment
RU—Rural
SE—Spectral efficiency
SFN—Single frequency network
SIB—System information block
SINR—Signal-to-interference-plus-noise ratio
SU—Suburban
U—Urban
UE—User equipment
WCDMA—Wideband Code Division Multiple Access

performance under various scenarios. eMBMS performance and use cases depend on many factors such as the frequency of operation, morphology of use, deployment considerations (e.g., antenna height, inter-site spacing dictated by unicast services), range of eMBMS service area and protection coverage, user equipment (UE) algorithms, and indoor versus outdoor use. Factors such as these are important for radio network designers. The impact of such factors is also addressed. The paper concludes with a discussion of the associated impact of LTE radio network engineering, and an estimate of eMBMS performance in a practical network consisting of a mixture of different geomorphology types.

Note that other broadcast technologies associated with mobile wireless networks have been proposed in the past, such as Digital Video Broadcast—Handheld (DVB-H) [14], the Broadcast/Multicast Services (BCMCS) for Code Division Multiple Access (CDMA2000) [9] system, Multimedia Broadcast Multicast Service (MBMS) for Wideband Code Division Multiple Access (WCDMA) [1], and MediaFLO* [21], although they have not been success stories. Unlike such previous attempts, eMBMS is tightly integrated and completely coexists with LTE. LTE, which is expected to be a great success since it is an undisputed 4G technology with worldwide support. eMBMS has the potential of riding on the technological coattails of LTE, while bringing new services to LTE customers and capacity relief to network operators.

eMBMS Overview

eMBMS is ideally suited to simultaneously deliver any common content to a large number of users within a contiguous region of adjoining cells. This is enabled by all of these cells acting in a

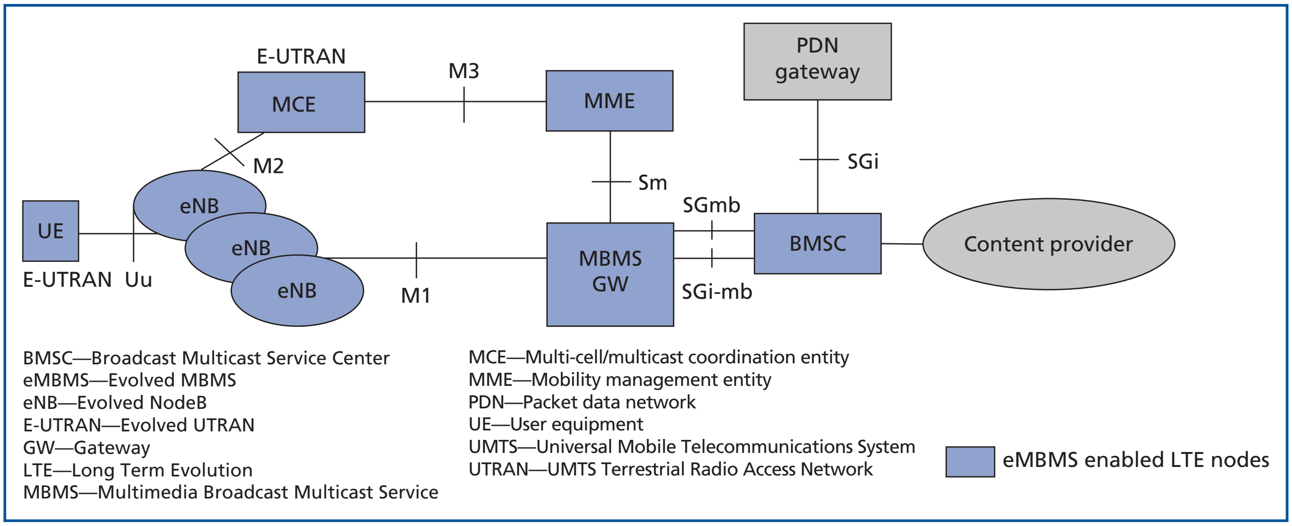


Figure 1.
eMBMS reference architecture.

coordinated single frequency network (SFN) arrangement, i.e., transmitting identical Orthogonal Frequency Division Multiplexing (OFDM) signals in a time synchronized manner. For this reason, the radio solution for eMBMS is known as Multicast Broadcast SFN (MBSFN). These identical signals combine over the air in a non-coherent manner at each of the recipient user antennas, resulting in improved signal-to-interference-plus-noise ratio (SINR). Thus, what is normally out-of-cell interference in unicast becomes a useful signal component in eMBMS. Support for eMBMS requires both synchronization at the physical layer as well as at the application layer across multiple cells that participate in an eMBMS service delivery, in order to ensure that both the OFDM symbols and the content that occupy it are properly time synchronized.

Given this, eMBMS is ideally suited to deliver any content that is of simultaneous interest to a large number of users in the service area. Examples of such services are broadcast content such as music and video, news/sports clips, broadcast/emergency notifications, push-to-talk (PTT) wherein one person communicates simultaneously to a large number of users, and media distribution such as software update/download. These different content types require varying levels of quality of service: for example, while PTT delivery may tolerate high block error rates (BLERs) of 10^{-2}, other services such as video content or software download typically require much lower error rates, and so additional application level forward error correction (FEC) and file repair protocols such as File Delivery over Unidirectional Transport (FLUTE) [19] are used to supplement the physical layer modulation and coding scheme (MCS) used by the eMBMS radio bearer.

eMBMS Architecture

The eMBMS system is defined in and relies on 3rd Generation Partnership Program (3GPP) specifications and Internet Engineering Task Force (IETF) Requests for Comment (RFCs). Some of the key references are [4–8, 15, and 19].

The reference architecture for eMBMS is given in **Figure 1.** As shown in the figure, eMBMS impacts several LTE and enhanced packet core (EPC) network elements (NEs). The eMBMS related functions are:

- *Broadcast Multicast Service Center (BMSC).* In the bearer plane, the BMSC is where content is ingested, and where bearer plane protocols that terminate on UE are processed, viz., FEC and FLUTE. The BMSC also provides a synchronization function to enable MBSFN transmission among the evolved NodeB (eNBs) base stations

(BS). In the control plane, the BMSC initiates session control messages to set up network resources.

- *Multimedia Broadcast Multicast Service (MBMS) gateway (MBMS-GW).* In the bearer plane, the MBMS-GW distributes broadcast content received from the BMSC towards the radio access network (RAN), i.e., eNBs using the Internet Protocol (IP) multicast transport. In the control plane, the MBMS-GW relays session control messages to the mobility management entity (MME), as well as creates IP multicast group associations to eNBs.
- *Mobility management entity (MME).* In the control plane, the MME relays session control messages toward multi-cell/multicast coordination entities (MCEs). The MME does not participate in the bearer plane.
- *Multi-cell/multicast coordination entity (MCE).* In the control plane, the MCE relays session control messages to eNBs, performs admission control on eMBMS sessions, and assigns uniform radio resources among MBSFN cells to ensure MBSFN operation. The MCE does not participate in the bearer plane.
- *eNB.* In the bearer plane, eNBs receive broadcast content from the MBMS-GW and transmit over the air. In the control plane, eNBs set up radio resources assigned by the MCE and convey session resources to UEs via over-the-air control channels such as system information blocks (SIBs) and multicast control channel (MCCHs).
- *Transport.* The transport network supports the bearer plane by building appropriate IP multicast trees from the eNBs that join an IP multicast group towards the source (i.e., MBMS-GW), and forwarding broadcast content from the MBMS-GW to eNBs that participate in the multicast group.
- *UE.* The user equipment is responsible for using application layer protocols to discover the desired eMBMS service identifiers and then use SIB information to determine the corresponding physical layer parameters for the broadcast transmission. The selected eMBMS radio interface is then terminated at the UE, along with service specific application layer error protection and recovery protocols, after using the appropriate content decoding process.

In LTE, eMBMS services are offered on a time-shared basis with unicast services. The frame structure for LTE frequency division duplexing (FDD) is illustrated in **Figure 2**. The LTE frame is subdivided into ten equal subframes of 1 millisecond each. In the release 9 version of the 3GPP specifications, some of the subframes (numbering 0, 4, 5, and 9) are reserved for unicast services and cell specific information and so may not be used to carry eMBMS transmissions. Any or all of the remaining six subframes may be allocated to eMBMS service. The UE is informed about which subframes are assigned to the eMBMS via a broadcast channel and the allocation can be changed dynamically at specified intervals. An eMBMS subframe consists of two slots with four to five eMBMS OFDM symbols in the first slot and six in the second slot. Each symbol is composed of a useful symbol duration of approximately 66.7 μs and is preceded by an "extended" cyclic prefix (CP) of approximately 16.7 μs. Note that this is in contrast to unicast subframes which consist of 14 OFDM symbols with the "normal" CP of approximately 4.7 μs. As can be seen in the case of eMBMS, provision has been made for a longer CP than unicast to accommodate a longer guard time, thus enabling more SFN signals from distant eNBs to contribute to useful signal energy.

Since the same signal must be received by all the intended recipients within the entire coverage area, the transmission format must be so chosen as to be successfully receivable at a specified quality (e.g., a BLER of 10^{-2}) over a specified coverage probability (e.g., 95 percent). Thus the modulation and coding scheme (MCS) must be appropriately chosen to meet these performance objectives, commensurate with the expected SINR achievable in the coverage area.

Performance Assessment

As explained above, the eMBMS radio solution is based on multiple BS cell sites transmitting identical time-synchronized OFDM symbols acting as an SFN. While SFN transmission is considered to be a novel

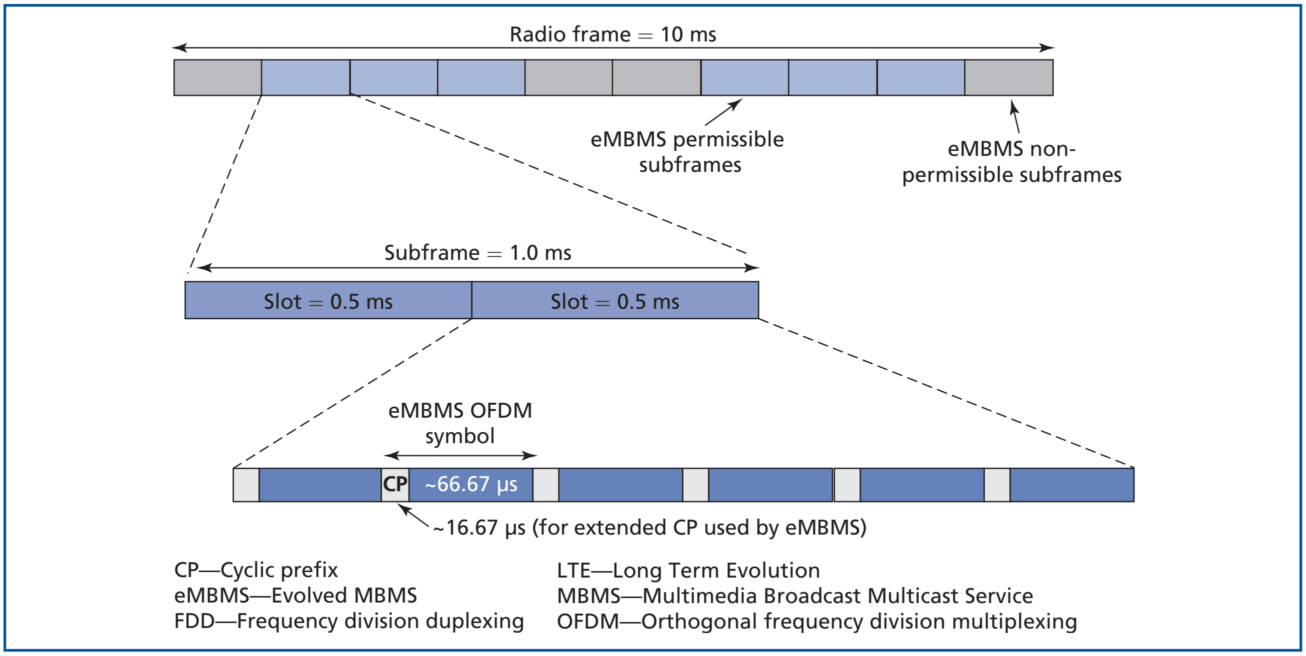


Figure 2.
LTE FDD downlink frame format.

solution in a mobile cellular network, the SFN technique has been used for some time in OFDM-based digital broadcast systems such as Digital Audio Broadcast (DAB) [12] and Digital Video Broadcast (DVB) for Terrestrial Networks (DVB-T) [13], and lessons learned from the broadcast industry may be usefully applied to study eMBMS performance.

Modeling Approach

The key issue impacting SFN-based OFDM performance assessment is the need to correctly model the impact of distant cell sites contributing to the SFN transmission, particularly in a case where these radio paths have either a shorter transmission delay than the receiver's reference path or a longer transmission delay than the "extended" CP period specified for eMBMS.

Figure 3 illustrates this effect, in which the mobile terminal is receiving identical but time shifted copies of the same broadcast signal from cell sites A, B and C. However, due to the effect of random shadow fading, the terminal receiver has synchronized to the current serving cell site B, resulting in the signal from cell site A arriving earlier than the serving cell, and the signal from cell site C arriving later than the serving cell. The net received signal is therefore going to show the additive benefit of useful signals from cell sites B and C, while the signal from cell site A will contribute partially to both useful signal and inter-symbol interference (ISI).

To study the impact of ISI in an SFN transmission system, we adopted a performance modeling technique originally proposed to model broadcast systems [10], [16], and [20]. This technique relies on a window function to model the impact of both early and late arriving SFN signal components on the net received signal quality measured in terms of SINR.

We define an empirical function w(t) such that,

$$w(t) = \begin{cases} 0 & t \leq -aT_u \\ \left(1 + \frac{t}{T_u}\right)^n & -aT_u < t \leq 0 \\ 1 & 0 < t \leq T_c \\ \left(1 - \frac{(t - T_c)}{T_u}\right)^n & T_c < t \leq T_c + aT_u \\ 0 & t > T_c + aT_u \end{cases} \quad (1)$$

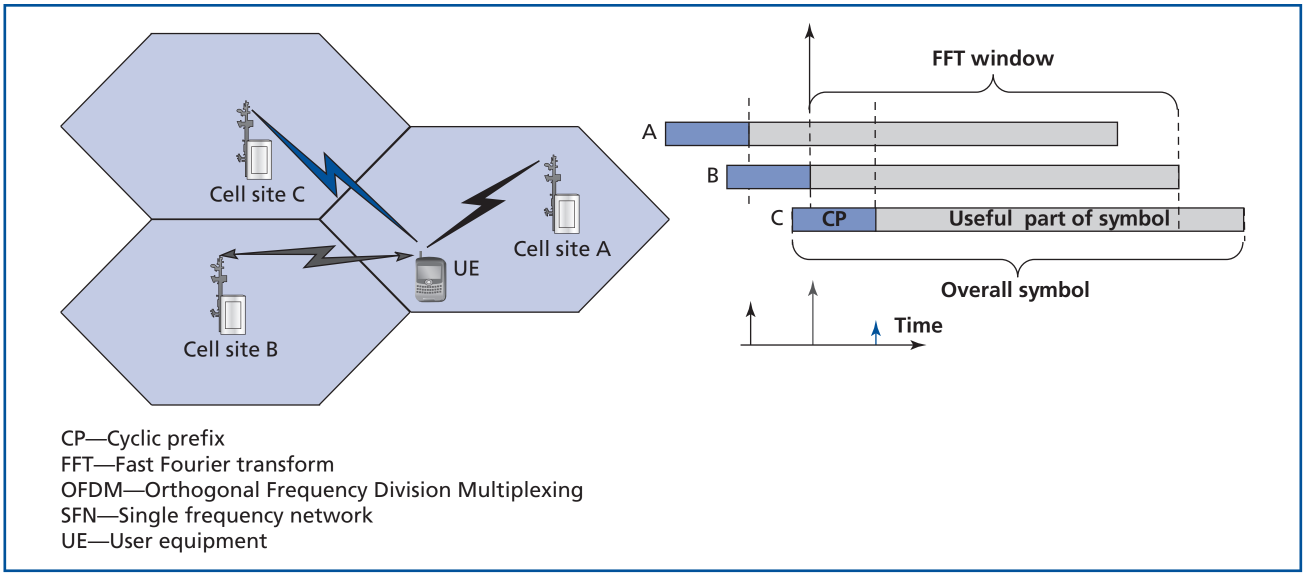


Figure 3.
Example for OFDM reception of SFN transmission from three cell sites.

where, T_u is the length of the useful part of the OFDM symbol, T_c is the length of the cyclic prefix of the OFDM symbol, and "a" and "n" are constants reflecting the nature of the particular OFDM receiver in the UE. In particular, these parameters describe the range in path delay over which equalization of multi-path and SFN components may be usefully resolved [16].

Using this window function, the useful signal and ISI as seen by a UE receiver at a particular location is defined to be:

$$S_{ijk} = C_{ijk}\, w(t_{ik} - t_0) \tag{2}$$

$$I^{ISI}_{ijk} = C_{ijk}\, (1 - w(t_{ik} - t_0)) \tag{3}$$

where, i is the index for cell site, j the index for sector, and k the index for path in a multi-path environment, t_0 is the reference delay of the receiver, t_{ik} is the path delay to the particular UE location, and C_{ijk} is the net received transmission power from the path contributing to the SFN signal, i.e.,

$$C_{ijk} = L_i\, h_{ijk} G_{ij} P_{ij} \quad \text{for all sector j contributing to SFN} \tag{4}$$

where, L_i is the path (including building penetration and body) gain, h_{ijk} is the fraction of the k^{th} path's gain relative to sum total of all the paths from the sector, P_{ij} is the transmit power, and G_{ij} is the net antenna gain (excluding any cable losses) to the UE.

Combining equation 1, equation 2, and equation 3 it may be observed that the w(t) window function is describing three possible situations:

1) Paths arriving within the period of cyclic prefix, T_c, after the delay of the selected serving cell, are assumed to contribute a useful signal. In this case, $w(t) = 1$ and so $S_{ijk} = C_{ijk}$ and $I^{ISI}_{ijk} = 0$.
2) Paths arriving within the transition periods of width aT_u either before the delay of the selected serving cell or after the period of cyclic prefix, T_c, are assumed to contribute to both useful signal and interference. This case models the presence of power from either the previous or next symbol within the OFDM receiver fast Fourier Transform (FFT) window period. For example, in the case of cell site A in Figure 3, part of the time shifted path results in both the current and adjacent symbols partially overlapping the FFT integration window.
3) Paths arriving either before or after the end of the transition period are assumed to only contribute interference. In such a case, $w(t) = 0$ and so $S_{ijk} = 0$ and $I^{ISI}_{ijk} = C_{ijk}$. This case models the failure of the OFDM receiver to extract any useful signal from a path for excessive delay compared to the serving cell.

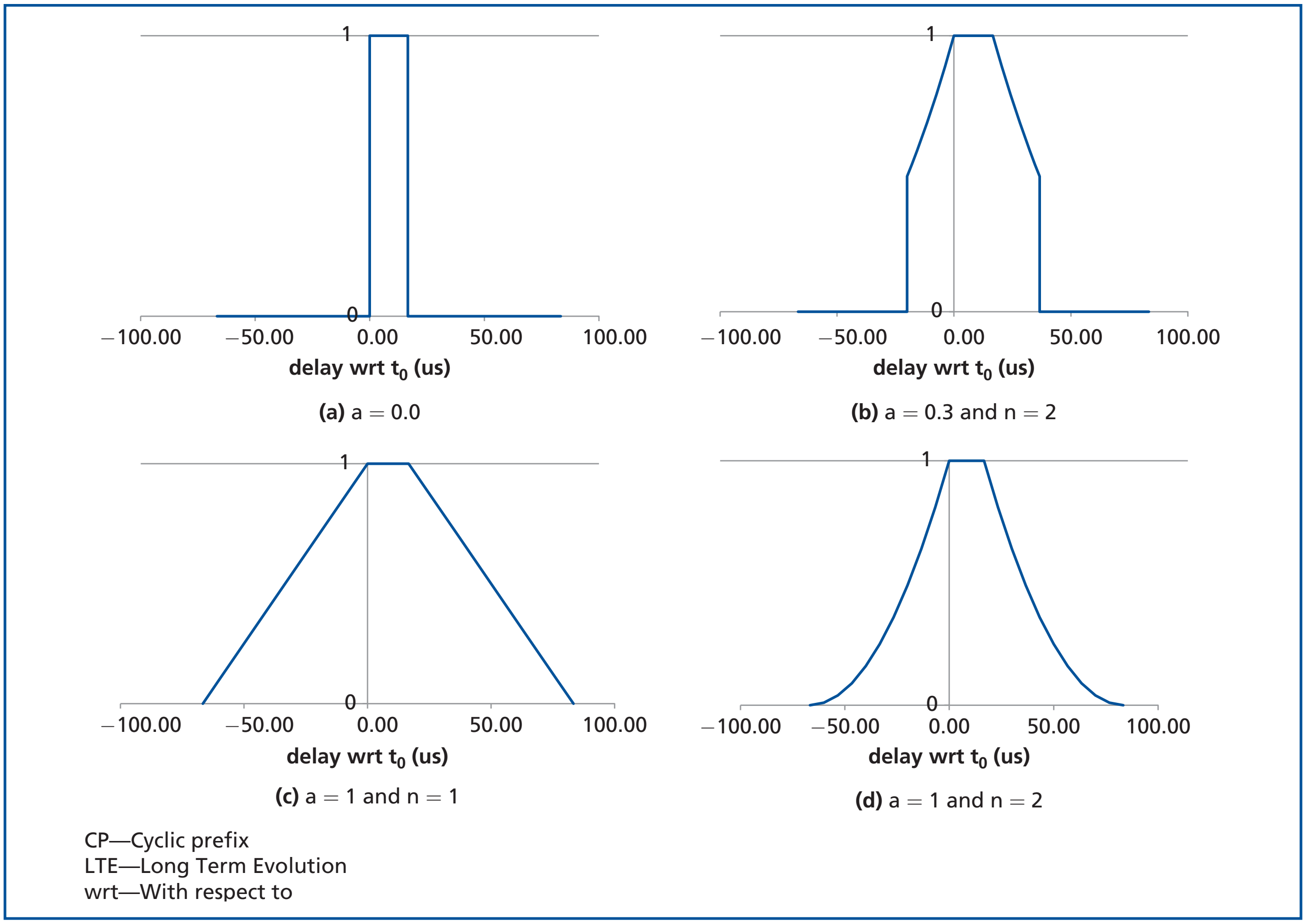


Figure 4.
Example of w(t) window function for LTE "extended CP" symbol.

Case 2 above may be understood to describe the combined impact of increasing power from the previous or next symbol falling within the FFT window, leading to a gradual increase in interference and loss of useful signal, and secondly, the impact of eventual loss of path detection by the receiver channel estimation process once the delay exceeds either $-aT_u$ before or $T_c + aT_u$ after the serving cell path arrival time. Brugger [10] notes that while $a = 1$ may be appropriate to model the DAB system that uses differentiation modulation, a lower value of $a = 0.3$ is more appropriate for DVB-T, which uses a design similar (coherent demodulation) to eMBMS, and so the same factors are assumed to apply to the LTE eMBMS waveform (see **Figure 4**). However, since the applicable factors depend on receiver design, we have investigated their performance sensitivity.

In addition to ISI amongst cell sites contributing to the SFN transmission, we also model the impact of potential non-SFN interference (NSI) from nearby cell sites that are not contributing to the SFN transmission (i.e., signals arriving from cell sites that are associated with a neighboring SFN zone, or unicast transmissions that are sharing the same radio resources but carrying an entirely different signal). In this case, all paths from non-SFN sites contribute fully to interference, and we define the NSI as seen by a receiver at a particular location to be:

$$I_{ijk}^{NSI} = L_i h_{ijk} G_{ij} P_{ij} \quad \text{for all sector j not contributing to SFN} \tag{5}$$

Combining these components and including the factor N for receiver noise over the system bandwidth, the net SINR for the signal received from all nearby cell sites as seen by a receiver at a particular location is then:

$$\mathrm{SINR} = \frac{\Sigma_i \Sigma_j \Sigma_k (S_{ijk})}{\Sigma_i \Sigma_j \Sigma_k (I_{ijk}^{ISI} + I_{ijk}^{NSI}) + N} \qquad (6)$$

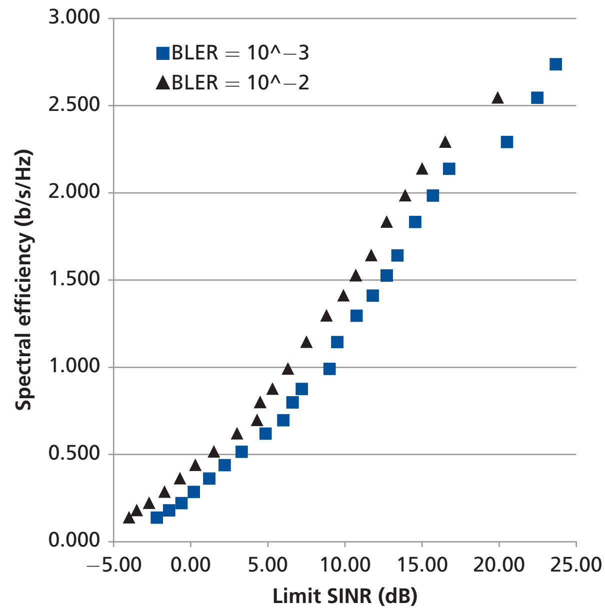
The SINR is therefore a function of the sector role (i.e., whether the sector is contributing as an SFN member, transmitting on an alternative physical channel, or not transmitting at all in the same subframe), the net received power and path delay from each cell site, and the overall reference delay t_0 selected by the receiver that defines the position of the FFT window. This last factor depends upon the physical layer synchronization algorithm in the terminal and so will be manufacturer dependent.

For this study, we assume that the eMBMS transmission subframes will be received using an FFT window aligned to the timing of the terminal's serving cell, which is assumed to be the strongest received path from the serving sector (e.g., path "p," sector "m" of a particular cell site "n"). A reasonable approximation of this process, referred to in this paper as "serving" is,

$$t_0 \equiv t_{pn}, \text{ such that } L_n\, h_{nmp}\, G_{nm}\, P_{nm} \geq L_i\, h_{ijk}\, G_{ij}\, P_{ij} \text{ for all } k \neq p,\ i \neq n \text{ and } j \neq m \qquad (7)$$

Note that in this case the serving sector is not necessarily the strongest overall contributing cell site and may not be the closest cell site.

Using this model, the overall performance of the eMBMS service may then be estimated by finding the distribution of the resulting SINR for all UE locations within a given zone used to collect statistics, and then searching for the limit value for which the coverage probability is greater than the required minimum (assumed to be greater than 95 percent in our analysis). This limit SINR value is then used to find the maximum possible MCS (modulation and coding scheme) that could be safely used for the given use case and target BLER, and hence the resulting spectral efficiency for the eMBMS service may be determined. The mapping of limit SINR to spectral efficiency (SE) in b/s/Hz is presented in **Figure 5** for



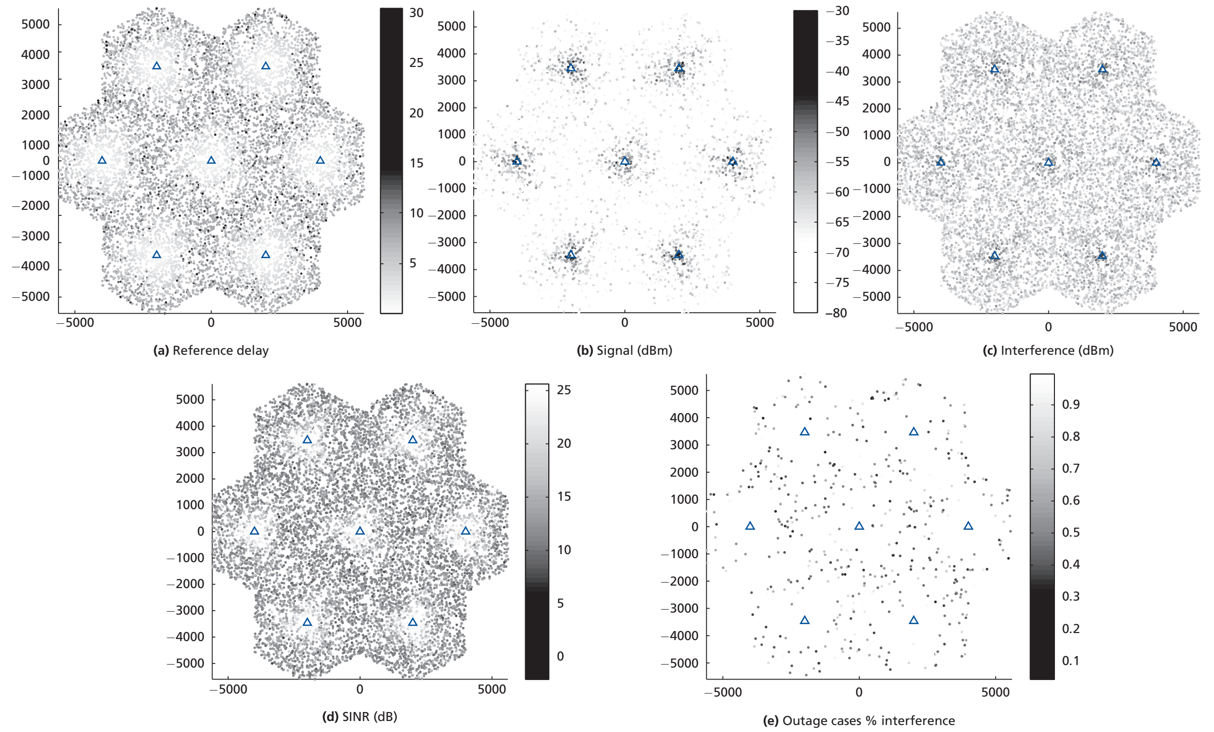
BLER—Block error rate
SINR—Signal-to-interference-plus-noise ratio

Figure 5.
Assumed mapping of limit SINR to spectral efficiency.

10^{-2} (i.e., 1 percent) and 10^{-3} (i.e., 0.1 percent) BLER using a representative wideband radio channel.

The overall modeling process is illustrated in **Figure 6** for the case of a 4 km inter site distance (ISD), 800 MHz carrier, 50 meter cell site antennas, 8 dB lognormal shadowing, 9 dB noise figure, 20 dB penetration loss, and a large SFN pattern. In each figure, an 8x8 km square showing a center cell site and six immediate neighbors provides an example of:

a) Selected reference delay. Near zero values may be observed around each cell site with progressively long delays in the cell edge zone. Note that significantly longer reference delays may be observed corresponding to cases where the propagation path to all of the two or three closest cell sites suffers from an adverse shadow fading, while a more distant cell site has a favorable shadow fading. Thus, the UE is being served by this more distant cell site.
b) Total received useful signal, showing the combined impact of shadowing and excessive delay compared to the selected reference delay.



ISD—Inter site distance SFN—Single frequency network SINR—Signal-to-interference-plus-noise ratio

Figure 6.
Example of overall modeling approach. For test case ISD = 4 km, 800 MHz carrier, 50 meter antenna height, 8 dB shadow fading σ, 20 dB penetration loss, large SFN pattern.

c) Total received interference, showing the impact of excessive delay compared to the selected reference delay.
d) Resulting SINR.
e) Analysis of locations with less than limit SINR, color coded to show if the location is suffering from lack of a useful signal and hence is noise limited or has excessive interference. Both noise and interference limited locations may be observed.

Assumptions and Validation

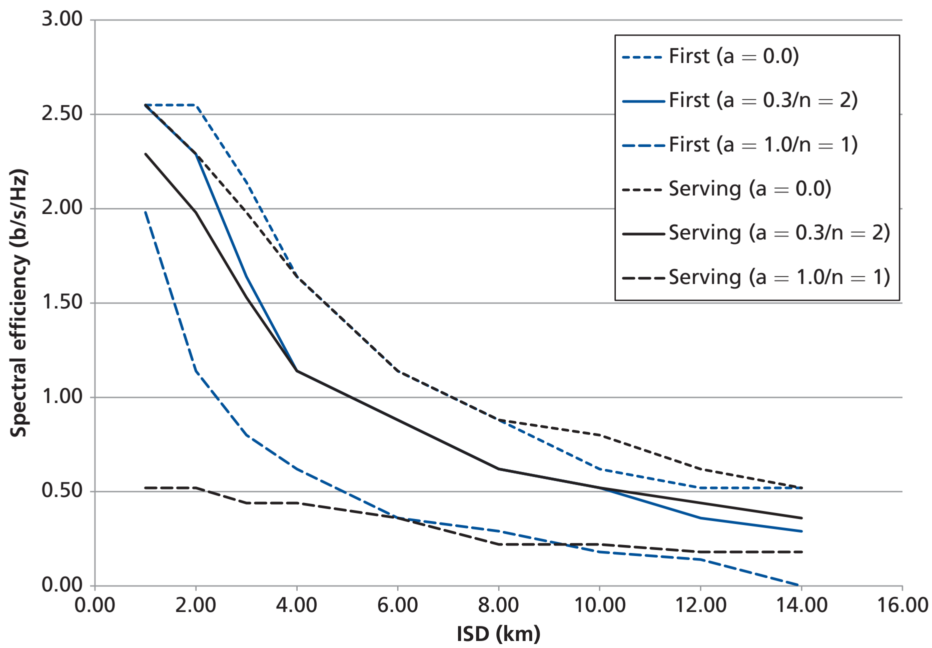
For most common parameters and assumptions, the usual simulation assumptions from 3GPP specifications TR 36.814 [3], TR 25.814 [1], and TR 30.03 [2] have been adopted as the baseline. See **Table I** for a few key ones.

The impact of the "a" and "n" parameters in the w(t) function and the interaction with the assumed terminal synchronization process is presented in **Figure 7**, wherein "first" implies that the UE always attaches to the closest sector, and hence to the first arriving signal, while "serving" refers to the unicast serving sector for that UE, and hence has the strongest arriving signal. Note that the "serving" model is believed to more accurately match realistic terminal behavior than the more simplistic "first" model. It is interesting to note that the well known but pessimistic "brick-wall" model for SFN reception (a = 0.0) shows very poor performance when the "serving" sector synchronization process defined in equation 7 is assumed, while this is not the case when a larger value of the "a" parameter such as a = 0.3, which is more realistic of real receivers, is assumed. This difference appears to be due to the finite probability that in a shadowing environment there will be locations where terminals tend to attach to more distant

Table I. Summary of key assumptions used in performance simulations.

Parameter	Default values	Remarks
Shadowing fading	Log-normal, $\sigma = 8$ dB	
Cross correlation between cell sites and sectors	0.5 (between different cell sites) 1.0 (between sectors on same cell site)	Correlated shadow fading values generated using a common random variable approach
Penetration loss	0 dB–20 dB	
Cell site height	15–50 meters	
Cell pattern	For large SFN: several cell site tiers around central cell site, each cell site consisting of three sectors. Other configurations described in text.	"Large SFN" case has all sectors contributing to SFN transmission
UE locations	Dropped randomly within the simulated area	Statistics only collected from center cell-site UEs
Propagation loss		Aligned to 3GPP macro model

3GPP—3rd Generation Partnership Project
SFN—Single frequency network
UE—User equipment



BW—Bandwidth
ISD—Inter site distance

Figure 7.
Impact of terminal synchronization process and w(t) parameter selection. For test case carrier = 800 MHz, BW = 10 MHz, antenna height = 50 meters, noise figure = 9 dB, penetration loss = 5 dB, shadow fading σ = 8 dB.

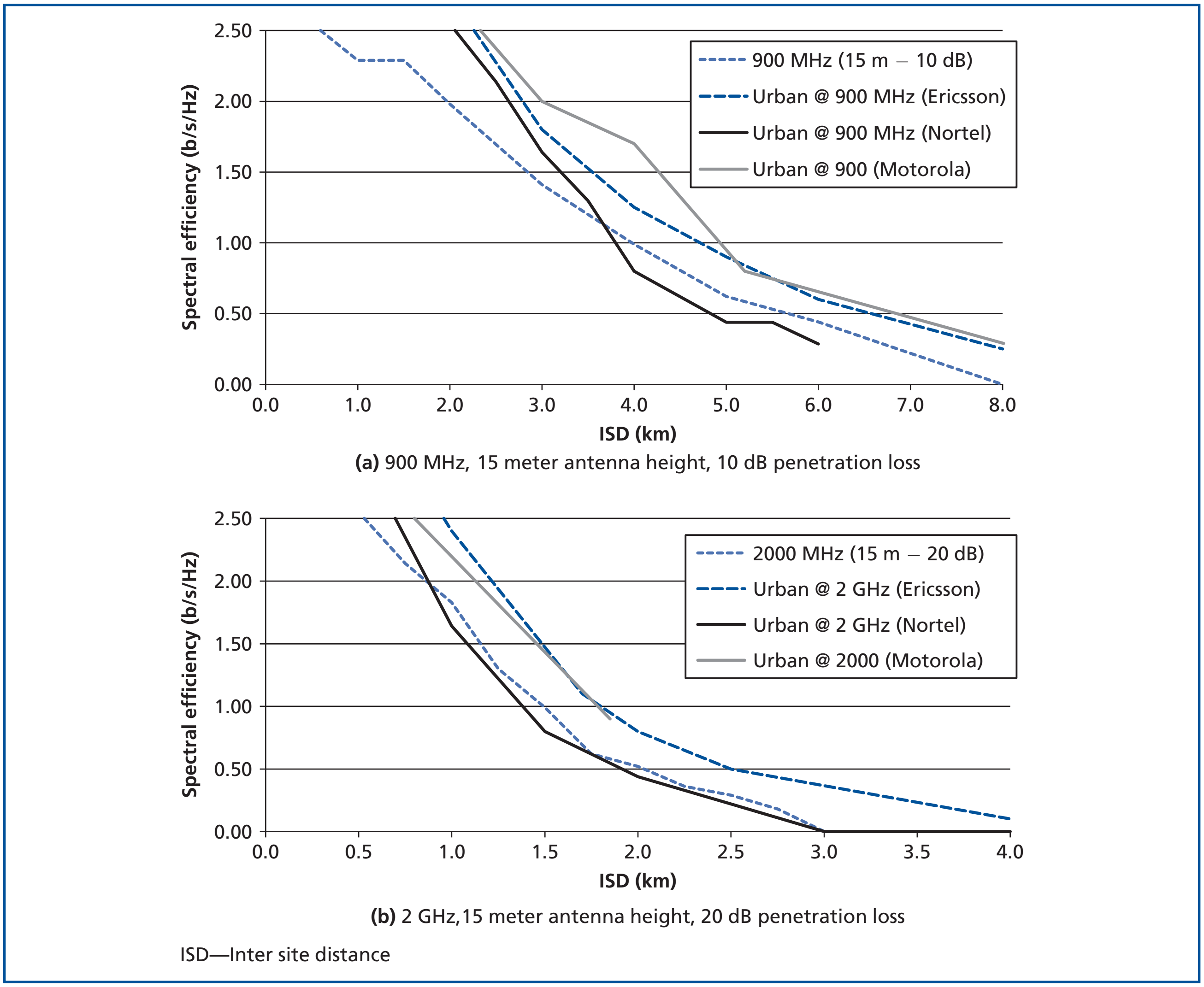
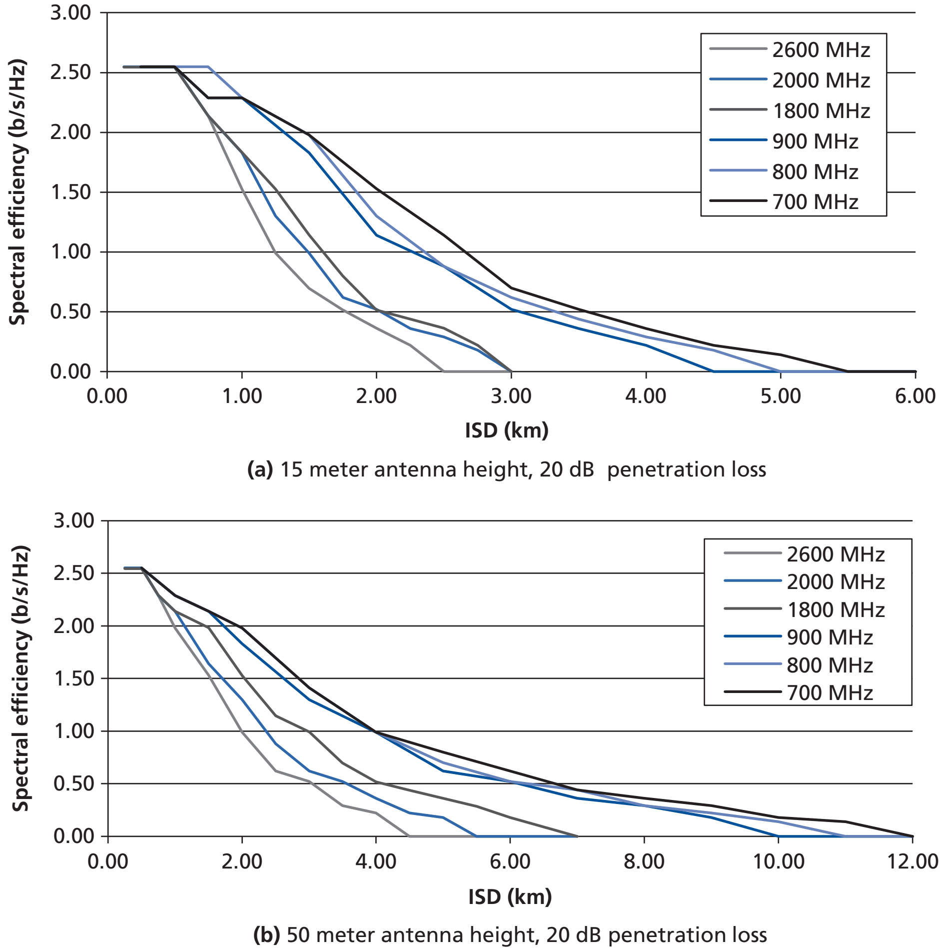


Figure 8.
Comparison of performance estimates with published literature at 900 MHz and 2 GHz.

but stronger cell sites. As a result, the nearer cell site signal arrives earlier than the reference timing point, leading to significant ISI from the earlier symbol that cannot be eliminated using the cyclic prefix. Since eMBMS performance is expected to be reasonable at short ISD**,** we then concluded that while the "brick-wall" model is incorrect, it is also inadequate in properly modeling the performance, and so a wider weighting function with a = 0.3 is assumed to be a closer representation of the expected performance. Note that a = 1 is presented just for comparison purposes for ideal UE performance, however it is not realistic of UE behavior using the LTE eMBMS modulation scheme.

eMBMS performance estimates have been compared with results published in the literature [11, 17, and 18] at both 900 MHz and 2 GHz (see **Figure 8**) with results using our model approach described above. Note that almost all of the above cited published results do not explicitly describe the assumed UE receiver and synchronization modeling approach. The one notable exception is [18], which



eMBMS—Evolved Multimedia Broadcast Multicast Service
ISD—Inter site distance

Figure 9.
MBMS performance over range of carrier frequencies.

appears to use a w(t)-based modeling approach, although it assumes that n = 1 and a = 1. Despite the potential differences among the considered cases, especially in the critical range of 1 b/s/Hz to 1.5 b/s/Hz where eMBMS systems are expected to be used in realistic use cases, our results are in agreement with previous results. At lower ISDs, where higher SEs manifest, our results are more conservative. This is expected and more realistic, since our model takes into account channel estimation degradation, receiver error floor performance, and other constraints.

Performance Estimates Under Ideal Hexagon Cellular Design Assumptions

Using the performance assessment model described above, the performance of the 3GPP eMBMS radio bearer is first assessed using “ideal” cellular design assumptions with an ideal hexagon cell site location pattern and a large SFN zone (i.e., all neighboring sites of a large number of tiers are assumed to be part of the same SFN zone).

Figure 9 presents estimates for eMBMS performance over the full range of likely LTE carrier frequencies (from 700 MHz to 2.6 GHz), using both

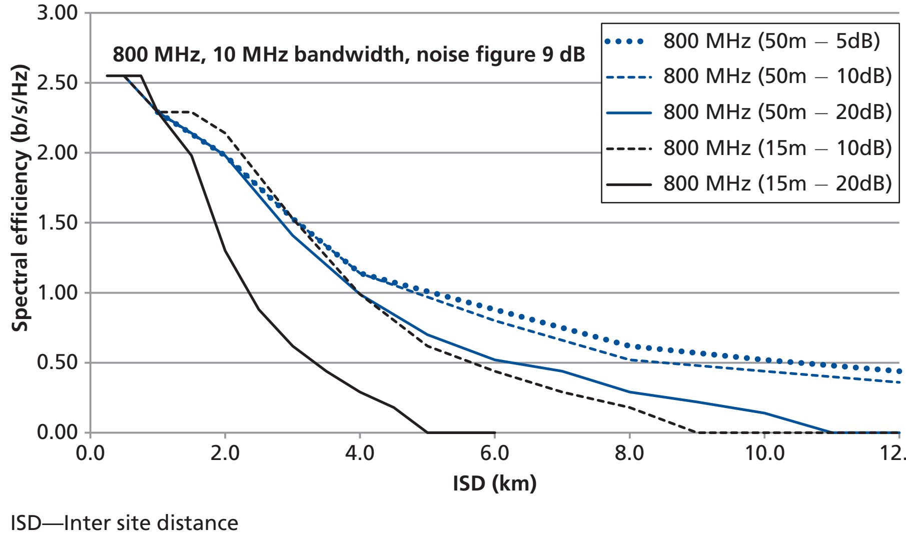


Figure 10.
Impact of penetration loss allowance.

15 meter and 50 meter antenna heights, and a building penetration loss of 20 dB. As should be expected, the lower bands and higher antenna cases perform best due to the superior received signal strength caused by more benign path losses. This effect may also be observed in **Figure 10,** which illustrates the improvement in eMBMS performance as the penetration loss allowance is reduced from 20 dB for "indoor" towards 5 dB, which is often assumed for "in car" coverage designs for the 800 MHz band using 15 meter and 50 meter cell sites. It is interesting to note that for this low band, the useful range that supports a wide variety of ISD use cases (up to 1.5 bps/Hz) aligns well with the change in coverage limits for different morphologies with:

- The typical dense urban (DU) use case often designed to achieve good "indoor" coverage with a 20 dB penetration loss allowance when using 15 meter cell site antennas, out to
- The typical capacity limited rural (RU) use case, which has design assumptions for 50-meter cell site antennas and relaxed "in-car" coverage requirements with a 5 dB penetration loss assumption.

Note, however, that rural design rules are unlikely to provide satisfactory eMBMS performance in very large coverage limited cells with greater than 10 km ISD. However, this is not critical because broadcast services could be maintained in this case using unicast bearers utilizing the inherent spare capacity of coverage limited cell sites.

Performance Estimates: Impact of Non-Ideal Conditions

This section describes the impact of non-ideal radio network conditions on the performance of eMBMS radio transmission. We address the specific issues of non-ideal cell site placement, the impact of reduced SFN zone, and multi-path radio channels.

In a practical network the cell site locations are not going to be ideally located, and so the net received signal over a large SFN zone will be affected due to non-ideal cell site placement. To investigate this issue we have simulated a non-ideal cell site grid with locations randomly dropped with a normal distribution in X and Y directions around the ideal locations. **Figure 11** illustrates the impact of this additional random process, and shows that the average and observed worst case performance compared to ideal placement are not significantly different for large SFN cases.

A second non-ideal issue to assess is the impact of reduced SFN area size. **Figure 12** shows the change in eMBMS performance seen by the center tri-sector cell site area when the number of neighboring sectors contributing to the SFN zone is reduced. We consider the following use cases, which are described in **Figure 13**:

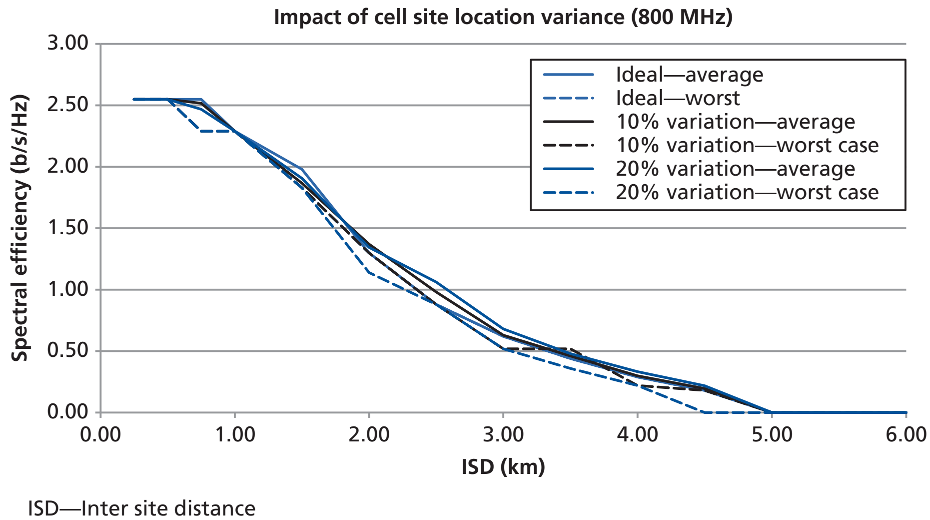


Figure 11.
Impact of non-ideal cell site placement.

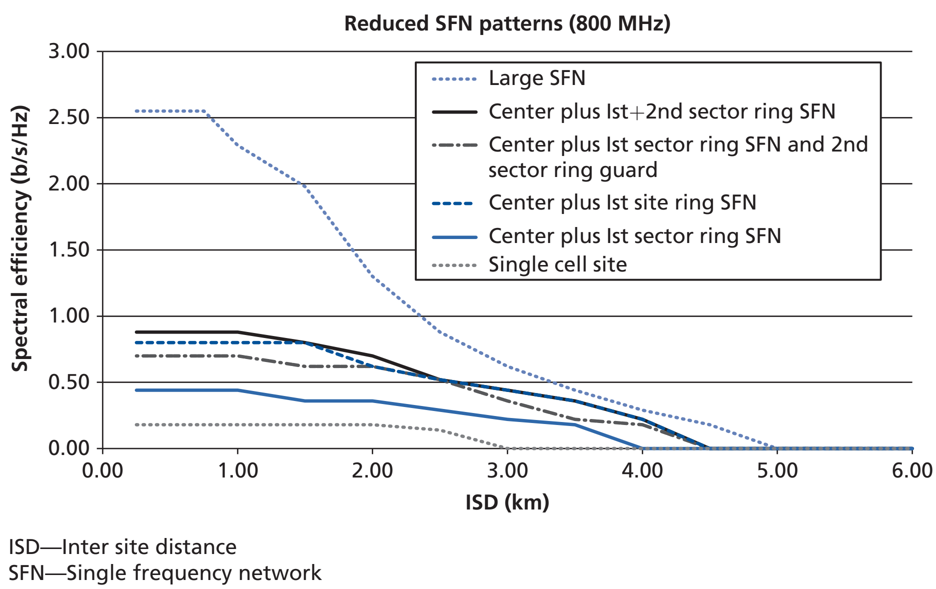


Figure 12.
Impact of reduced SFN size.

- *Large SFN*. The center cell and all neighboring tri-sector cell sites for several tiers are all members of the same SFN zone.
- *Center plus 1st and 2nd sector rings.* The center cell plus 24 closest sectors from the neighboring cell sites are members of the same SFN zone, which is surrounded by a ring of 30 interfering sectors.
- *Center plus 1st sector ring and 2nd sector ring guard.* The central cell site plus nine closest sectors from the first six neighbors are members of the same SFN zone, which is surrounded first by a ring of 15 "guard" sectors that are not transmitting anything during the eMBMS subframe and then a second ring of 30 interfering sectors.

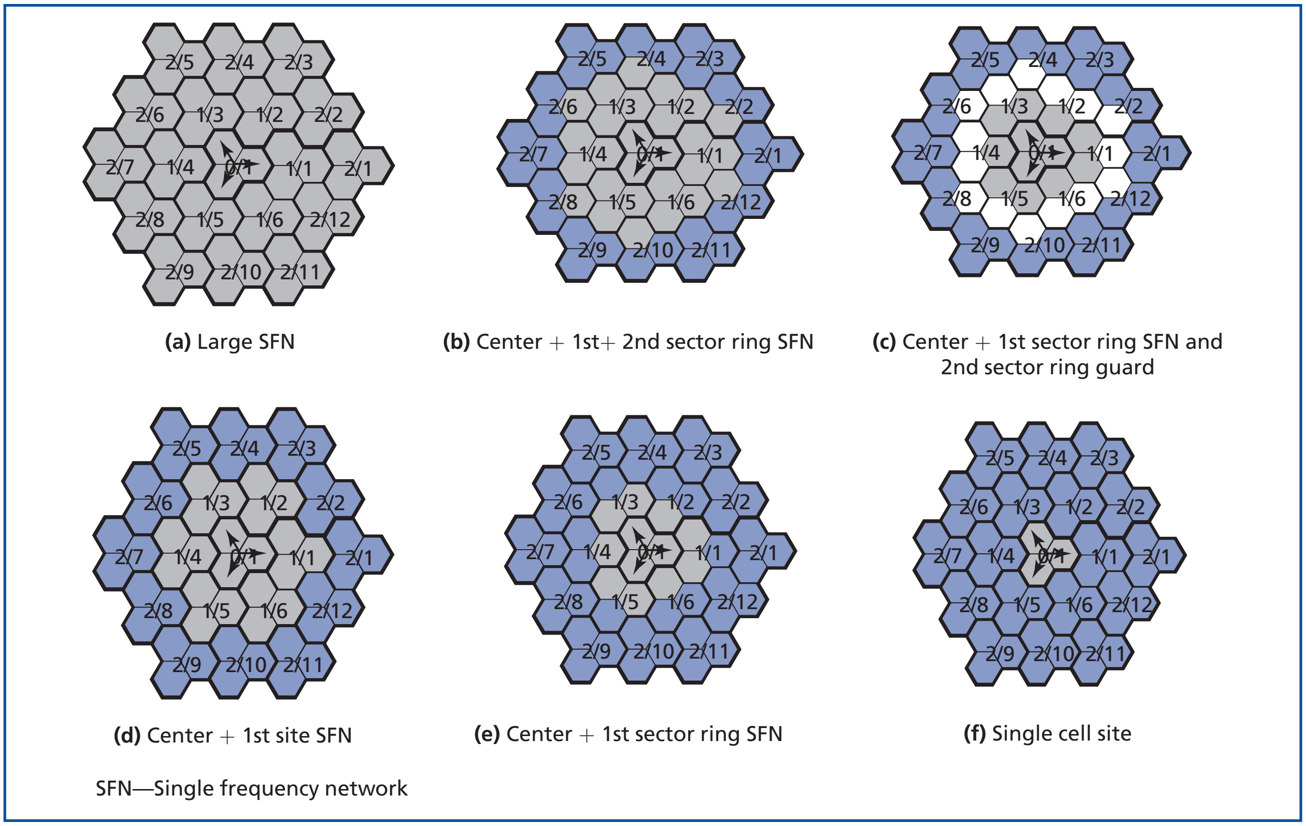


Figure 13.
SFN patterns.

- *Center plus 1st site ring.* The central cell site plus closest six neighboring cell sites are members of the same SFN zone surrounded by 12 interfering tri-sector cell sites.
- *Center plus 1st sector ring*. The central cell site plus nine closest sectors from the first six neighbors are members of the same SFN zone, which is surrounded by a total of 45 interfering sectors.
- *Single cell site.* The tri-sector center cell site forms an SFN area which is surrounded by 18 neighboring interfering tri-sector cell sites, that is, a three sector SFN area surrounded by a total of 54 interfering sectors.

Comparing the performance for the different SFN patterns, we make the following observations:

- The single cell site SFN case has very poor performance due to excessive interference from surrounding cell sites and is not recommended.
- All of the small SFN area cases show significantly lower performance compared with the baseline "large SFN" case, and so local eMBMS services should only be offered where there is significant local demand for the same content and little or no interest in the remainder of a metropolitan area.
- The option of selectively adding individual sectors from a given cell site to a given SFN is recommended since there are gains to be had for every additional ring of SFN sectors.
- Likewise, the adoption of "guard" sectors transmitting neither eMBMS nor interference during a subframe used by a neighboring cell site or sector for eMBMS transmissions appears to offer an advantage compared to a direct transition between SFN membership and interference. This approach is likely to result in lower interference toward neighboring SFN areas, and so the requirements for overlapping SFN areas could be minimized leading to a tighter packing of eMBMS transmission reuse patterns.

Table II. Typical radio network engineering design considerations.

Parameter	Dense urban (DU)	Urban (U)	Suburban (SU)	RU (inner)	RU (outer)
Antenna height (m)	15	15	50	50	50
Penetration loss (dB)	20	20	20	10	10
Coverage limit (km)					
800 MHz	1.6	2.5	5.5	15	15
1800 MHz	0.8	1.2	2.7	9	9
2600 MHz	0.5	0.8	1.9	6.5	6.5
Typical cell site grid ISD (km)	0.5	1.0	2.0	3.0	15.0

ISD—Inter site distance

Radio Network Engineering Considerations

When implementing eMBMS services, the radio network engineering team must go through the following steps:

- Design the MBSFN areas and estimate the limit SINR per MBSFN area for the different types of services (nationwide versus local) and for the different frequency bands,
- Estimate the MCS from the limit SINR and required BLER per session, and derive throughput per subframe over the allocated frequency bandwidth,
- Compute the resources (number of subframes and repetition periods) required to offer the throughput necessary for eMBMS services/sessions using the previously estimated throughput per subframe,
- Verify whether or not there are enough remaining resources to handle the expected unicast demand for services,
- If not, the design of MBSFN areas needs to be revisited.

Designing an MBSFN area is the new challenge faced by radio network engineers. It was demonstrated previously that SE performance in a given MBSFN area is dependent on the ISD, along with many other factors. When we revisit the typical cell sizes and associated ISD of a cellular network delivering unicast services for different frequency bands and morphology, we observe that the cell sizes are coverage dependent for suburban (SU) and rural (RU) installations, with mainly propagation constraints dictating the cell sizes. On the other hand, in dense urban (DU) and urban (U) installations, cells sizes are decided based on capacity requirements with a "cell site grid" setting the actual ISD, reflecting the end point of successive cell splitting actions due to the current and/or previous capacity limits of the mobile network. This is illustrated in **Table II,** which presents typical radio network engineering parameters in terms of antenna heights, penetration loss margin, carrier frequency dependent range limit, and typical ISD for DU, U, SU, and RU morphologies, with the latter zone split into an "inner" region designed to meet a capacity limit and an "outer" region designed to meet only the coverage limit. **Table III** presents the corresponding performance of eMBMS for these typical radio network engineering values using the results from the eMBMS performance assessment presented in Figure 9 and Figure 10.

From the results presented in Table III, it seems to be intuitive to define as many MBSFN areas as there are morphologies with each zone operating at its optimal eMBMS spectral efficiency. In practice this is not the case because a realistic radio network design has to account for a mixed environment for neighboring zones designed to meet DU, U, SU, and/or RU needs at applicable performance limits. For unicast services this is not an issue since each cell site may be individually optimized to meet its local environment. However, as Figure 12 demonstrates, this is not the case for eMBMS services as boundaries between different SFN areas should be minimized to avoid performance loss due to high levels of NSI from nearby cell sites. Consequently, one has to abandon the approach of segregation of MBSFN area per

Table III. Estimated eMBMS performance.

Parameter	Dense urban (DU)	Urban (U)	Suburban (SU)	RU (inner)	RU (outer)
Typical cell site grid ISD (km)	0.5	1.0	2.0	3.0	15.0
eMBMS performance (b/s/Hz)					
800 MHz	2.55	2.3	2.0	1.5	–
1800 MHz	2.55	1.8	1.5	1.0	–
2600 MHz	2.55	1.5	1.0	0.5	–

eMBMS—Evolved MBMS
ISD—Inter site distance
MBMS—Multimedia Broadcast Multicast Service

Table IV. Estimated likely eMBMS spectral efficiency.

Frequency	Net SE (b/s/Hz)	Limit case	Max ISD (km)
800 MHz	1.5	Rural (inner)	3
1800 MHz	1.5	Urban	2
2600 MHz	1.5	Urban	1

eMBMS—Evolved MBMS
ISD—Inter site distance
Max—Maximum
MBMS—Multimedia Broadcast Multicast Service
SE—Spectral efficiency

morphology and find a way to obtain rather homogeneous performances over the different morphologies in the same MBSFN area.

This leads to a more realistic eMBMS design where a common MBSFN area is designed to offer a grade of service and supportable data rates in terms of a minimum per cell site coverage (i.e., 95 percent of locations), and so a common eMBMS operating mode is selected based on the worst case in the desired service area. Using such a deployment model, **Table IV** provides the expected spectral efficiency for different carrier frequencies that would be expected in a mixed morphology environment using the typical radio network design parameters from Table II. Note that while the same overall spectral efficiency is shown for 800 MHz, 1800 MHz, and 2600 MHz, only low bands such as 800 MHz could offer this performance across an entire city and the surrounding rural area. On the other hand, the higher bands such as 1800 MHz and 2600 MHz are likely to offer a reduced coverage area with useful eMBMS services available only out to *suburban* areas for 1800 MHz and restricted to *urban* areas for 2600 MHz, with unicast bearers required to deliver multimedia services in other lower density areas if a low band such as 800 MHz is not available for eMBMS.

Conclusions

This paper has presented a brief description of the eMBMS subsystem that has been defined by 3GPP to offer an in-band broadcast bearer for the LTE radio access system. We presented our performance modeling approach and corresponding assessment under both ideal and more realistic conditions, and then offered an initial analysis of the impact of eMBMS service on LTE radio network engineering.

Performance results show that eMBMS is not an efficient solution to offer contiguous nationwide broadcast services. This is because in the vast expanse outside metropolitan and surrounding areas the ISDs are large where eMBMS supportable data rates are low. However, it may be used efficiently across entire metropolitan and surrounding "capacity limited" rural areas where using a low radio band such as 700 MHz or 800 MHz offers an impressive SE of 1.5 b/s/Hz. Similar spectral efficiency performance may also be expected at higher bands such as 1800 MHz or 2.6 GHz. However, in this case, the MBSFN service area would need to be limited to the dense urban and, for 1800 MHz service, suburban morphologies. This is, however, not necessarily a significant restriction because this restricted area is where unicast traffic loads are expected to be highest and hence the area where eMBMS based traffic offload would be most welcome.

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*Trademark

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