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Juan Vargas*†, Cédric Thienot *, Xavier Lagrange†
*Enensys Technologies, Rennes, France
{juan-carlos.vargas-rubio, cedric.thienot}@enensys.com
†IMT Atlantique/IRISA, Rennes, France
xavier.lagrange@imt-atlantique.fr

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**Abstract**

Mission Critical Communication (MCC) Services are currently provided through secure and reliable Professional Mobile Radio (PMR) dedicated networks. These services include voice, data and video delivery. During an emergency, timely access to video streaming can increase situational awareness and enhance life-saving operations. Therefore, to improve the capabilities of PMR networks and benefit from the advantages of mutualization, standard cellular technologies based on 4G and 5G were adopted for MCC. In particular, the evolved Multimedia Broadcast Multicast Service (eMBMS) is suitable for the transmission of group communication services. There are two broadcast transmission modes proposed in eMBMS: Multicast Broadcast Single Frequency Network (MBSFN) and Single-Cell Point-to-Multipoint (SC-PTM). In this paper, we compare MBSFN, SC-PTM and Unicast (UC) in Mission Critical (MC) scenarios from a resource use perspective. More precisely, we calculate the system spectral efficiency in each mode and estimate the number of users per square kilometer demanding the same MC service from which MBSFN and SC-PTM become more efficient than UC. Results show that SC-PTM is the best solution for locally restricted and small-scale emergencies while MBSFN is more suitable for emergencies during massive events or wide-area scenarios.

5G, 4G, LTE, Mission Critical Communications (MCC), MBSFN, SC-PTM, Multicast, Broadcast, Unicast, PMR.

## 1 Introduction

Mission Critical Communications (MCC) refer to the timely and reliable exchange of information between first responders in situations where human life and other values for society are at risk [1]. MCC can take place in different scenarios. Emergencies can affect a small geographical area or an entire city. Additionally, the number of MC users changes according to the severity and scale of the emergency. According to [2], over 1000 officers including companies of specialist riot teams and 1400 stewards were on duty in the surroundings of the biggest stadium in France during a massive event in 2020. In emergency conditions, people of rescue or security teams should share information in real time. Group communications, intended to distribute the same content to multiple users in a controlled manner, are thus of prime importance to ensure efficient operations.

MCC depend on secure Professional Mobile Radio (PMR) networks. The first PMR technologies were based on specific waveforms and multiplexing methods and offered mainly voice services but they had a limited possibility to support data services. In parallel, public networks advanced rapidly with the deployment of 3G, 4G-LTE and nowadays 5G. 4G and 5G networks and terminals offer bitrates and functionalities superior to those of PMR. Because of this, the working group PMR-TCCA (Tetra & Critical Communication Association) partnered with 3GPP to achieve in Release 13 the definition of high-bitrate PMR services working on LTE bands. These services include MC Push-to-Talk (MCPTT) and group communication. Afterwards, in Release 14 two new MC services were specified: MCVideo and MCData. These MC services are not as exigent in terms of latency as ultra-reliable low-latency communication (URLLC) services but they can be bandwidth consuming. Therefore, LTE Broadcast, defined for the first time in Release 9, was adopted to support PMR group communication. Today, there exist two Broadcast (BC) technologies used in mobile networks: Multicast Broadcast Single Frequency Network (MBSFN) and Single-Cell Point-to-Multipoint (SC-PTM).

MBSFN transmission consist on a group of synchronized cells that transmit the same waveform at the same time to a potentially infinite number of users. An MBSFN-capable User Equipment (UE) treats the signals

*Contact Author

from these cells as multipath components of a single transmission. The cluster of cells that are synchronized and perform transmission of the same content form an MBSFN Area. The main advantage of MBSFN transmission is the reduction of interference since signals from neighboring cells become useful. This increases the SINR perceived by UEs. However, BC transmissions do not benefit from link adaptation. Therefore, they are aimed to cover UEs with the worst channel conditions, i.e., users at the border of the MBSFN area with the lowest SINR. Additionally, MBSFN transmissions are performed on a subframe basis: they occupy the entire system bandwidth and use the extended cyclic prefix. MBSFN and Unicast (UC) transmissions cannot be multiplexed in the same subframe.

The most recent BC technique, proposed in Release 13, is SC-PTM. With SC-PTM the BC transmission is performed by a single cell. The advantages of SC-PTM are: the broadcast area can be dynamically decided cell by cell, radio resources can be shared between SC-PTM and UC in the same subframe, use of normal Cyclic Prefix, no need of synchronization among cells and shorter setup latency [3]. However, SC-PTM transmissions do not benefit from link adaptation as UC or interference reduction and increased SINR as MBSFN.

Unicast transmission mode is the most widely used in cellular networks. With this mode, the data rate received by the user is a function of its channel conditions thanks to link adaptation. Additionally, it can benefit from technologies as beamforming, which is out of the scope of this paper. Nevertheless, if many users demand the same service, repeated data is transmitted as many times as the number of UE requesting the same content, which is an inefficient use of radio resources.

Each transmission mode has advantages and disadvantages that make them suitable for certain scenarios and inefficient in others. There isn't a transmission mode that is the best in all cases. The problem lies in defining what is the most efficient transmission mode for a certain Mission Critical scenario based on its characteristics: Base Station (BS) density, UE density, size of the Mission Critical Area and the MBSFN area, propagation effects, bitrate requirement and available radio resources.

The 3GPP presents in [3] a comparison between SC-PTM and MBSFN for public safety. They conclude that SC-PTM is more efficient that MBSFN when UEs are only located in some cells of the MBSFN area. They also observed that SC-PTM is more efficient than single cell MBSFN. However, they consider that all cells in the MBSFN area participate in the MBSFN transmission even if they do not have UEs camped on them. Additionally, their simulations use a regular hexagonal model with an inter-site distance of 1732m (a BS density of $\sim$0.4 BS/km$^2$), which is low compared to actual deployments in big cities. At last, they consider at most 20 UEs per cell, which is low for MC Scenarios in massive events. The work in [4] compares MBSFN, SC-PTM and UC in terms of radio quality, system spectral efficiency and cell coverage. Their study considers 4 UE/cell in most simulations and a BS density of $\sim$0.31 BS/km$^2$ with omnidirectional antennas. Under this assumptions they conclude that SC-PTM outperforms both UC and MBSFN in terms of System Spectral Efficiency (SSE). In our study we prove that this affirmation do not always hold true, specially for MC scenarios with high user densities and BS densities.

In this study, we propose a model to calculate the SINR perceived by a MC user in MBSFN (considering interfering reserved cells), SC-PTM and UC based on [5]. We use a Poisson Point Process (PPP) distribution for the location of the three-sector BS. Subsequently, we propose a resource utilization model based on [4] and [5] in which the SSE and the User Threshold are the two metrics used to compare MBSFN and SC-PTM transmission modes. The results, obtained through Monte-Carlo simulations, establish a foundation to decide which is the most efficient transmission mode according to the characteristics of the Mission Critical scenario.

The remainder of this paper is structured as follows: section 2 presents the mathematical equations used to model the system, including the calculations of SINR. In section 3 we develop a model used to compare the efficiency of MBSFN, SC-PTM and UC modes in terms of system spectral efficiency and user threshold. Afterwards, simulation results are presented and discussed in section 4. Finally, the conclusions are presented in section 5.

# 2 System model

The propagation model is based on Okumura-Hata-Cost231 with shadowing and fading following the 3GPP reference model [6]. Three-sector base stations are considered with adapted antennas. To take into account the irregularity of operational networks, we consider BSs located following a PPP of density $\lambda_{\mathrm{BS}}$ . It is assumed that all cells use the same transmission power and carrier frequency.

In UC and SC-PTM modes each UE receives the content from its serving cell, i.e., the cell from which the UE perceives the highest SINR. All the other cells generate interference. On the other hand, in MBSFN mode the UE receives the signals from all the cells belonging to the MBSFN area, except for the MBSFN Area Reserved Cells. In our study, we consider that a cell in the MBSFN area becomes a reserved cell if there are not any UE interested in the BC content camped on it. Additionally, we consider that reserved cells are allowed to transmit for other services and therefore, generate interference [7]. We denote the cells from the MBSFN area that contribute to the MBSFN transmission as $N_{\mathrm{SFNon}}$. Interfering reserved cells are denoted by $N_{\mathrm{SFNint}}$.

Therefore the total number of cells in the MBSFN area is $N_{\mathrm{SFN}} = N_{\mathrm{SFNon}} + N_{\mathrm{SFNint}}$.

In this study we do not consider guard cells or additional transmitting cells in MBSFN mode. The findings from [3], [4] and our own simulations proved that the SINR gain of using guard cells or additional cells does not compensate the additional use of radio resources.

## 2.1 Propagation Effects

We consider the following propagation effects: in addition to a distance-based path-loss with factor $k$ and exponent $\alpha$, fading is modeled as an exponential random variable (r.v.) $h$ with unit rate, and shadowing corresponds to a Log-Normal r.v. $\exp(\chi)$, with $\chi$ following a normal distribution with zero mean and variance $\sigma^2$. Shadowing is usually characterized in terms of the geometric standard deviation in dB of the log-normal distribution $\sigma^*_{\mathrm{dB}}$. We have $\sigma^*_{\mathrm{dB}} = 10\log_{10}\sigma^*$ and $\ln\sigma^* = \sigma$, therefore $\sigma^*_{\mathrm{dB}} = \frac{10}{\ln 10}\sigma$. Additionally, the r.v. $\chi$ is composed of a correlated part ($\chi_c$), to account for the obstacles close to the receiver, and a non-correlated part ($\chi_i$), corresponding to the obstacles independent for each BS, then, $\chi = \chi_c + \chi_i$ and $\sigma^2 = \sigma_c^2 + \sigma_i^2$. The correlation coefficient is defined as $\rho = \frac{\sigma_c^2}{\sigma^2}$.

## 2.2 Antenna Gain

In each cell, the antenna gain in the direction $\theta$, measured from the antenna boresight, is calculated as stated in [6]

$$G_{\mathrm{dB}}(\theta) = G_{\mathrm{A}} - \min\left\{12\left(\frac{\theta}{\theta_{3\mathrm{dB}}}\right)^2, G_{\mathrm{FB}}\right\}, \tag{1}$$

where $G_{\mathrm{A}}$ is the antenna gain in the boresight direction in dB, $\theta_{3\mathrm{dB}}$ is the 3 dB beam width, $G_{\mathrm{FB}}$ is the antenna front to back ratio and $\mid\theta\mid \leq 180°$.

## 2.3 SINR Derivation

### 2.3.1 MBSFN

The number of cells in the MBSFN Area that participate in the BC transmission is denoted as $N_{\mathrm{SFNon}}$. The cells outside the MBSFN area and the reserved cells generate interference. Thus, the useful signal power received by a UE in MBSFN mode is given by

$$P_{\mathrm{SFN}} = P_{\mathrm{tx}} k e^{\chi_c} \sum_{i,j \in N_{\mathrm{SFNon}}} \delta_i r_i^{-\alpha} h_i e^{\chi_i} G(\theta_{i,j}), \tag{2}$$

where $P_{\mathrm{tx}}$ is the transmission power, sub-indexes $i$ and $j$ denote the BS and the cell, respectively, such that $1 <= j <= 3$. $r_i$ is the distance between the UE and BS $i$. Factor $\delta_i$ is used to determine the usefulness of the signals coming from the tri-sectored antenna placed on BS $i$ [8]. It is calculated as

$$\delta_i = \begin{cases} 1 & 0 \leq r_i - r_s \leq cT_{\mathrm{CP}} \\ (1 + \frac{T_{\mathrm{CP}}}{T_{\mathrm{u}}} + \frac{r_s - r_i}{cT_{\mathrm{u}}})^2 & cT_{\mathrm{CP}} < r_i - r_s \leq cT_{\mathrm{f}} \\ 0 & r_i - r_s > cT_{\mathrm{f}} \end{cases}, \tag{3}$$

where $r_s$ is the distance between the UE and its serving BS, $c$ is the speed of light, $T_{\mathrm{CP}}$ is the length of the cyclic prefix, $T_{\mathrm{u}}$ is the useful OFDM symbol time and $T_{\mathrm{f}} = T_{\mathrm{CP}} + T_{\mathrm{u}}$ is the total symbol time.

The interference for a UE receiving in MBSFN mode is defined as

$$\begin{aligned} &I_{\mathrm{SFN}} \\ &\quad = P_{\mathrm{tx}} k e^{\chi_c} \left( \sum_{i,j \in N_{\mathrm{SFNon}}} (1 - \delta_i) r_i^{-\alpha} h_i e^{\chi_i} G(\theta_{i,j}) + \sum_{i,j \notin N_{\mathrm{SFNon}}} r_i^{-\alpha} h_i e^{\chi_i} G(\theta_{i,j}) \right). \end{aligned} \tag{4}$$

Then, the SINR perceived by a UE receiving in MBSFN mode is calculated as $S_{\mathrm{SFN}} = \frac{P_{\mathrm{SFN}}}{P_{\mathrm{N}} + I_{\mathrm{SFN}}}$, where $P_{\mathrm{N}}$ denotes the noise power.

### 2.3.2 SC-PTM and Unicast

In SC-PTM mode, only the serving cell provides useful signal power and all the others generate interference. The useful power received by a UE in SC-PTM mode can be calculated as

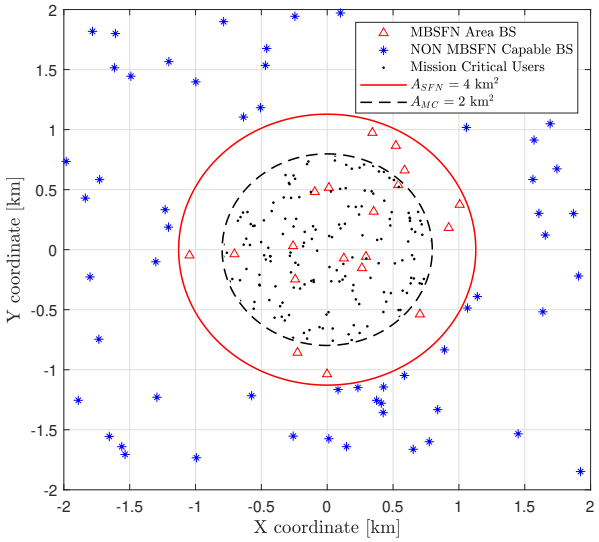


Figure 1: MBSFN capable BS in the MBSFN Area and MC users in the Mission Critical Area considering $\lambda_{\text{BS}} = 4$ BS/km$^2$ and $\lambda_{\text{UE}} = 100$ UE/km$^2$.

$$P_{\text{SC}} = P_{\text{tx}} k e^{\chi_c} r_s^{-\alpha} h_s e^{\chi_s} G(\theta_{s,s}), \tag{5}$$

where the sub-index $s$ denotes the serving cell and its corresponding BS. On the other hand, the interference perceived by a UE is defined as follows:

$$I_{\text{SC}} = P_{\text{tx}} k e^{\chi_c} \sum_{j, i \neq s, s} r_i^{-\alpha} h_i e^{\chi_i} G(\theta_{i,j}), \tag{6}$$

therefore, the SINR perceived by a user in SC-PTM mode is given by $S_{\text{SC}} = \frac{P_{\text{SC}}}{P_{\text{N}} + I_{\text{SC}}}$. Similarly, UC transmissions take place in a single cell and all other cells are interferes. Therefore the SINR perceived by a UE in Unicast mode can be derived in the same manner, $S_{\text{UC}} = S_{\text{SC}}$.

# 3 Radio Resource utilization

This section describes the resource utilization model used to compare the radio efficiency of MBSFN, SC-PTM and UC transmission modes. Since this study is centered on Mission Critical Communications, we fix an exigent coverage requirement of 99% (4% higher than in [3]). We define the area where the MC users (e.g., firemen) are located as the Mission Critical Area. In our study, this area is a disk and users are assumed to be uniformly distributed in the disk, see Fig. 1. In all the scenarios, we consider the transmission of a single content common to all the MC users. Users are located following a PPP of density $\lambda_{\text{UE}}$. We denote the number of MC users in the MC area as $N_{\text{u}}$. For each transmission mode we derive the expressions for the SSE and we present the equation for the ratio between radio resources and capacity.

## 3.1 Resource utilization in MBSFN mode

When an MBSFN available content is to be transmitted, the cells in the MBSFN Area that have MC users camped on them start the MBSFN transmission. The target SINR to cover ($S_{\text{mSFN}}$) is fixed as the lowest SINR among the 99% of these UE with the best channel conditions.

We calculate the SSE based on the Shannon Theorem. The capacity of a system ($C$) in bits per second (bits/s) is calculated as $C = W \log_2(1 + S)$, where $W$ denotes the system bandwidth and $S$ the SINR. We denote the radio resources used for MBSFN transmission as $W_{\text{SFN}}$. Thus, the SSE in MBSFN mode for a certain network deployment and MC users location is calculated as

$$E_{\text{SFN}} = \frac{C}{W_{\text{SFN}}} = \frac{6}{7} \log_2(1 + S_{\text{mSFN}}), \tag{7}$$

where the factor $\frac{6}{7}$ accounts for the longer cyclic prefix with MBSFN. Then, we take the expected value over several network deployments with the same $\lambda_{\text{BS}}$ and $\lambda_{\text{UE}}$ to obtain the average SSE in MBSFN mode

$\overline{E_{\mathrm{SFN}}} = \mathbb{E}[E_{\mathrm{SFN}}]$. Since $\mathbb{E}[1/E_{\mathrm{SFN}}] \neq 1/\mathbb{E}[E_{\mathrm{SFN}}]$, we define the average ratio between radio resources and capacity in MBSFN mode as

$$\Gamma_{\mathrm{SFN}} = \frac{W_{\mathrm{SFN}}}{C} = \mathbb{E}\left[\frac{1}{E_{\mathrm{SFN}}}\right], \tag{8}$$

which is useful to calculate the User threshold in section 3.4.

## 3.2 Resource utilization in SC-PTM mode

A cell transmitting in SC-PTM mode fixes the target SINR to cover ($S_{\mathrm{mSC}}$) based on the 99% coverage requirement. The SSE for a certain network deployment and MC users location is calculated as

$$E_{\mathrm{SC}} = \frac{C}{W_{\mathrm{SC}}} = \log_2(1 + S_{\mathrm{mSC}}). \tag{9}$$

We assume that all cells are SC-PTM capable. Then, we take the expected value over several network deployments with the same $\lambda_{\mathrm{BS}}$ and $\lambda_{\mathrm{UE}}$ to obtain the average SSE in SC-PMT mode $\overline{E_{\mathrm{SC}}} = \mathbb{E}[E_{\mathrm{SC}}]$. Finally, the average ratio between radio resources and capacity is given by

$$\Gamma_{\mathrm{SC}} = \frac{W_{\mathrm{SC}}}{C} = \mathbb{E}\left[\frac{1}{E_{\mathrm{SC}}}\right]. \tag{10}$$

## 3.3 Resource utilization in unicast mode

The UC mode uses link adaptation techniques and the radio resources per cell are shared among the users. Therefore the spectral efficiency is calculated for each MC user as $E_{\mathrm{UE}} = \frac{C}{W_{\mathrm{UE}}} = \log_2(1 + S_{\mathrm{UC}})$, where $W_{\mathrm{UE}}$ is the bandwidth allocated to the user and $S_{\mathrm{UC}}$ the SINR. Each cell fixes the minimum SINR to cover ($S_{\mathrm{mUC}}$) according to the coverage requirement. To calculate the SSE in UC mode for a certain network deployment and MC users location we average over all the values of SINR from $S_{\mathrm{mUC}}$ to the highest measured SINR

$$E_{\mathrm{UC}} = \mathbb{E}\left[\frac{E_{\mathrm{UE}}}{N_{\mathrm{u_{cell}}}}\middle| S_{\mathrm{UC}} \geq S_{\mathrm{mUC}}\right], \tag{11}$$

where $N_{\mathrm{u_{cell}}}$ is the number of users per cell. Therefore, the average SSE in unicast mode is calculated as $\overline{E_{\mathrm{UC}}} = \mathbb{E}[E_{\mathrm{UC}}]$. Additionally, the average ratio between radio resources and capacity in UC is calculated as:

$$\Gamma_{\mathrm{UC}} = \frac{\overline{W_{\mathrm{UE}}}}{C} = \mathbb{E}\left[\frac{1}{E_{\mathrm{UE}}}\middle| S_{\mathrm{UC}} \geq S_{\mathrm{mUC}}\right], \tag{12}$$

where $\overline{W_{\mathrm{UE}}}$ denotes the average radio resources per UE in UC. The same reasoning can be used to to estimate the the ratio between radio resources and capacity for users that remain in UC mode after MBSFN activation ($\Gamma_{\mathrm{UCo}}$). We denote the average radio resources per UE for theses users as $\overline{W_{\mathrm{UEo}}}$. The sub-index o stands for Outside the MBSFN area.

## 3.4 User Threshold

We define the User Threshold as the number of users per square kilometer demanding the same MC service from which MBSFN or SC-PTM become more efficient than UC from a resource utilization perspective.

A scenario that, to the best of our knowledge, has not been considered in previous works on the use of MBSFN transmission in MC Communications is: ***What happens with the MC users that request a content available in MBSFN mode but are camped in cells outside the MBSFN Area?*** In this study we examine two possibilities: 1) The SINR perceived by the UE from the active cells in the MBSFN area is higher than the minimum SINR targeted by the MBSFN transmission. In that case the UE starts a handover procedure and choose a serving cell among those in the MBSFN area to receive the content in BC mode. 2) The SINR perceived by the UE from the cells in the MBSFN area is lower than the minimum SINR targeted by the MBSFN transmission. Then, the UE remains receiving in UC mode from its serving cell. The fraction of MC users in the MC area that receive the content in BC mode after MBSFN activation is denoted by $\gamma_{\mathrm{SFN}}$ such that $0 \leq \gamma_{\mathrm{SFN}} \leq 1$.

### 3.4.1 Unicast to MBSFN

The comparison in terms of radio resource utilization between UC mode only and activating the MBSFN transmission is as follows:

$$N_{\mathrm{u}}\overline{W_{\mathrm{UE}}} > N_{\mathrm{SFNon}}W_{\mathrm{SFN}} + (1 - \gamma_{\mathrm{SFN}})N_{\mathrm{u}}\overline{W_{\mathrm{UEo}}}. \tag{13}$$

Table 1: Simulation parameters

| Parameter | Value |
|---|---|
| Total simulation area | 100 $\text{km}^2$ |
| System Bandwidth ($W$) | 20 MHz |
| Carrier Frequency ($f_c$) | 700 MHz |
| BS Transmission Power ($P_{\text{tx}}$) | 40 W |
| Trisectored antenna gain ($G_{\text{A}}$) | 15 dBi |
| Antenna frontback ratio ($G_{\text{FB}}$) | 20 dBi |
| 3 dB beam width ($\theta_{3\text{dB}}$) | 65° |
| Useful OFDM Symbol Time ($T_{\text{u}}$) | 66.7µs |
| Cyclic Prefix Length ($T_{\text{CP}}$) | 16.67µs |
| Shadowing Standard Deviation ($\sigma_{dB}$) | 10 dB |
| Shadowing Correlation Coefficient ($\rho$) | 0.5 |
| Noise Power ($P_{\text{N}}$) | −98 dBm |
| Path Loss Exponent ($\alpha$) | 3.76 |
| Path Loss Factor ($k$)[1] | 0.2630 |

[1] For distance in meters.

The user threshold for MBSFN ($U_{\text{T}_{\text{SFN}}}$) is the value of $N_{\text{u}}$ for which (13) is an equality. Thus, we obtain $U_{\text{T}_{\text{SFN}}}$ by solving (13) for $N_{\text{u}}$ and replacing $\overline{W_{\text{UE}}}$ and $W_{\text{SFN}}$ using (8) and (12) assuming the same target capacity ($C$) for unicast and MBSFN:

$$U_{\text{T}_{\text{SFN}}} = \frac{N_{\text{SFNon}}\Gamma_{\text{SFN}}}{A_{\text{MC}}(\Gamma_{\text{UC}} - (1-\gamma_{\text{SFN}})\Gamma_{\text{UCo}})}, \tag{14}$$

where $A_{\text{MC}}$ is the size of the MC area in $\text{km}^2$. $U_{\text{T}_{\text{SFN}}}$ is the exact number of MC users demanding the MC service from which MBSFN becomes more efficient that UC while $\lambda_{\text{UE}}$ is the average number of MC users on field.

### 3.4.2 Unicast to SC-PTM

Using SC-PTM, all the MC users are served in BC mode since there are not limitations in terms of broadcast area. Thus, the comparison in terms of radio resource utilization between UC and SC-PTM is as follows

$$N_{\text{u}}\overline{W_{\text{UE}}} > N_{\text{SC}}W_{\text{SC}}, \tag{15}$$

where $N_{\text{SC}}$ is the number of cells that transmit in SC-PTM mode. We obtain the User Threshold for SC-PTM ($U_{\text{T}_{\text{SC}}}$) using a similar procedure to the one used to obtain (14):

$$U_{\text{T}_{\text{SC}}} = \frac{N_{\text{SC}}\Gamma_{\text{SC}}}{A_{\text{MC}}\Gamma_{\text{UC}}}. \tag{16}$$

# 4 Simulation Results

In the first simulation we calculate the CDF of the SINR perceived by the UE when using each transmission mode. To do so, we use the Monte Carlo method. For a given set of system parameters ($\lambda_{\text{BS}}$, $\lambda_{\text{UE}}$, $A_{\text{SFN}}$, $A_{\text{MC}}$) we run several iterations and calculate the SINR perceived by the UEs in each mode based on the equations presented in section 2.3. To be compliant with 3GPP standards, most of the simulation parameters were taken from [6, Table C.1] and are given in Table 1.

Fig. 2 presents the CDF of the minimum SINR to cover in MBSFN ($S_{\text{mSFN}}$) in different scenarios and the CDF of $S_{\text{UC}}$. We see that for the same $\lambda_{\text{BS}}$ and $\lambda_{\text{UE}}$ values, $S_{\text{mSFN}}$ is higher when increasing the MBSFN area size ($A_{\text{SFN}}$). A SINR gain of ∼2.5dB is obtained when $\lambda_{\text{BS}} = 4$ BS/$\text{km}^2$ and $\lambda_{\text{UE}} = 100$ UE/$\text{km}^2$. At the same time, it is observed that the effect of the UE density changes depending on the BS density. When $\lambda_{\text{BS}} = 4$ BS/$\text{km}^2$ and for the same $A_{\text{SFN}}$, increasing the UE density results in a higher SINR. A gain of 3.35 dB is obtained when $A_{\text{SFN}} = 8$ $\text{km}^2$. This is because the more users in the MC area the higher number of active cells in the MBSFN area ($N_{\text{SFNon}}$). On the contrary, when $\lambda_{\text{BS}} = 1$ BS/$\text{km}^2$, increasing the UE density results in a lower SINR. In this case, $N_{\text{SFNon}}$ does not increase significantly because the cells cover a larger surface and the new users are camped on the already active cells. Furthermore, the probability of having users at the border of the MBSFN area increases. In other words, to increase the SINR in MBSFN mode, for a high UE density it is convenient to have a high BS density and for a low UE density it is better to have a low BS density.

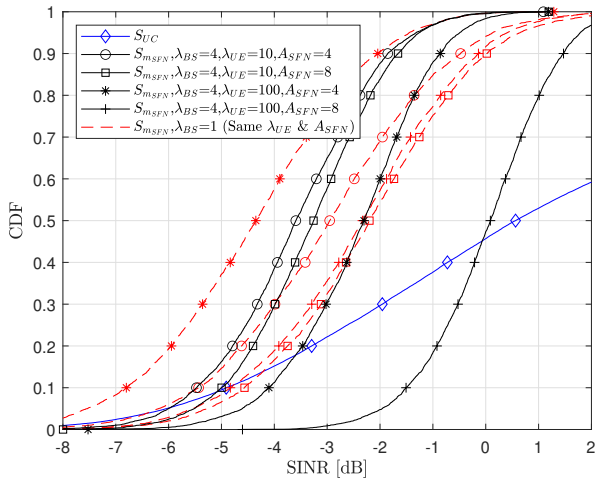


Figure 2: CDF of the minimum SINR to cover in MBSFN mode ($S_{\text{mSFN}}$) and CDF of the SINR in UC ($S_{\text{UC}}$) for different scenarios considering $A_{\text{MC}} = 4$ km$^2$. $\lambda_{\text{BS}}$ in BS/km$^2$, $\lambda_{\text{UE}}$ in UE/km$^2$ and $A_{\text{SFN}}$ in km$^2$.

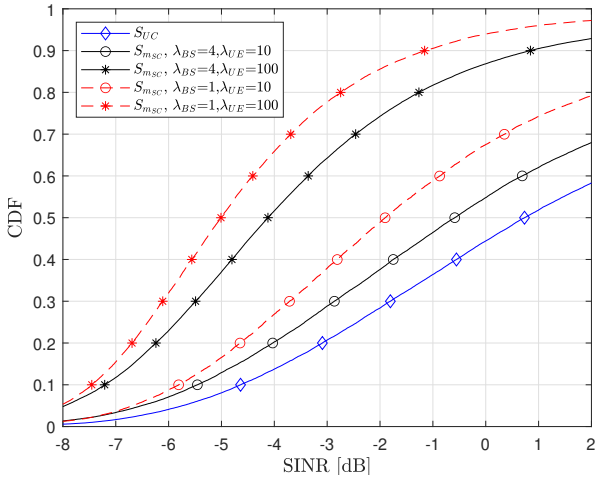


Figure 3: CDF of the minimum SINR to cover in SC-PTM mode ($S_{\text{mSFN}}$) and CDF of the SINR in UC ($S_{\text{UC}}$) for different scenarios considering $A_{\text{MC}} = 4$ km$^2$. $\lambda_{\text{BS}}$ in BS/km$^2$ and $\lambda_{\text{UE}}$ in UE/km$^2$.

Additionally, we appreciate that in most cases the target SINR in MBSFN is lower than the SINR in Unicast. However, for high $\lambda_{\text{BS}}$, $\lambda_{\text{UE}}$ and $A_{\text{SFN}}$ values, the median $S_{\text{mSFN}}$ value is close the median $S_{\text{UC}}$ value.

The CDF of the minimum SINR to cover in SC-PTM ($S_{\text{mSC}}$) are presented in Fig. 3. The simulations proved that when transmitting in SC-PTM mode we get a better performance when having a high BS density and low UE density. A gain $>$ 1dB can be obtained when increasing $\lambda_{\text{BS}}$ from 1 BS/km$^2$ to 4 BS/km$^2$. At the same time, a maximum gain of 4.8dB is obtained when reducing the UE density from 100 UE/km$^2$ to 10 UE/km$^2$. This is because the UEs receive a higher useful signal power from its serving cell when having a high BS density. Additionally, having less UE per cell reduces the probability of them being at the cell border. As expected the target SINR in SC-PTM mode ($S_{\text{mSC}}$) is lower than $S_{\text{UC}}$.

The System Spectral Efficiency for each transmission mode is presented in Fig. 4. We consider $\lambda_{\text{BS}} =$ 4 BS/km$^2$ and $\lambda_{\text{UE}} = 100$ BS/km$^2$. The ratio between the MC area and the MBSFN area is denoted as $\delta_{\text{MC}}$. First, notice that the SSE in SC-PTM is $\sim$ 0.2 bit/s/Hz higher than in UC for all the MC area sizes. The SSE in UC is reduced as the number of users per cell ($N_{\text{u}_{\text{cell}}}$) increases, as stated in (11). Furthermore, we see that the smaller the MC area the higher the SSE for SC-PTM and UC. Doubling the size of the MC area reduces the SSE by $\sim$0.05 bit/s/Hz. As seen before, SC-PTM and UC benefit from a low number of users. On the other hand, the SSE in MBSFN mode increases by $\sim$0.2 bit/s/Hz when doubling the size of the MC area and MBSFN area. Additionally, we see that for each MC area there is a threshold for the MBSFN area size from which the SSE stops increasing. This is because cells located far from the MC area are not selected as serving cells by the UEs and therefore do not participate in the MBSFN transmission. We also run simulations considering $\lambda_{\text{UE}} = 10$ BS/km$^2$. In that case, the SSE in MBSFN mode was below 0.5 bit/s/Hz for all the $A_{\text{MC}}$ and $\delta_{\text{MC}}$ values while the SSE for UC was above 1.2 bit/s/Hz and above 1.3 bit/s/Hz for SC-PTM.

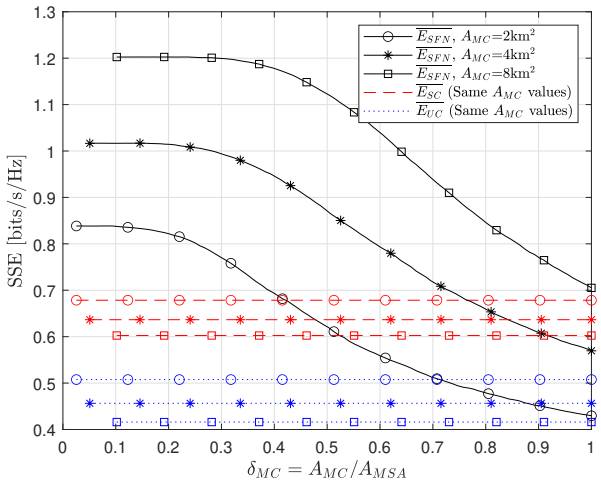


Figure 4: System Spectral Efficiency in MBSFN, SC-PTM and Unicast transmission modes for different scenarios considering $\lambda_{\mathrm{BS}} = 4$ BS/km$^2$ and $\lambda_{\mathrm{UE}} = 100$ UE/km$^2$.

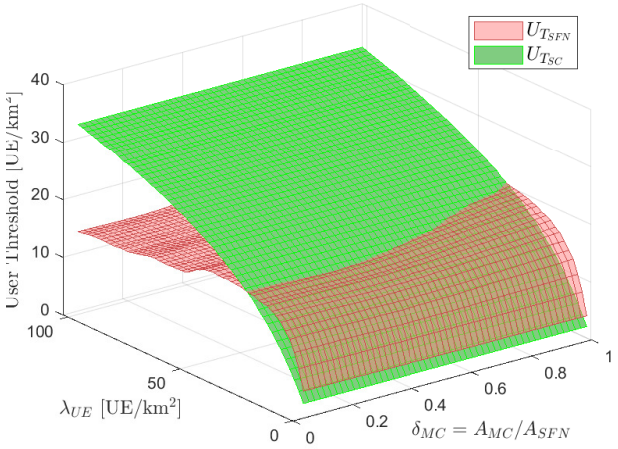


Figure 5: User threshold for MBSFN ($U_{\mathrm{T_{SFN}}}$) and SC-PTM ($U_{\mathrm{T_{SC}}}$) for different scenarios considering $\lambda_{\mathrm{BS}} = 4$ BS/km$^2$ and $A_{\mathrm{MC}} = 4$ km$^2$.

At last, the User Thresholds for MBSFN ($U_{\mathrm{T_{SFN}}}$) and SC-PTM ($U_{\mathrm{T_{SC}}}$) are presented in Fig. 5. We consider $\lambda_{\mathrm{BS}} = 4$ BS/km$^2$ and $A_{\mathrm{MC}} = 4$ km$^2$. If $\delta_{\mathrm{MC}} = 1$, the user threshold for MBSFN is higher than for SC-PTM when $\lambda_{\mathrm{UE}} < 38$ UE/km$^2$. For $\lambda_{\mathrm{UE}} = 38$ UE/km$^2$ and $\delta_{\mathrm{MC}} = 1$ we get $U_{\mathrm{T_{SFN}}} = U_{\mathrm{T_{SC}}} = 21$ UE/km$^2$ ($\sim$2UE/cell). If $\lambda_{\mathrm{UE}} > 38$ UE/km$^2$ then $U_{\mathrm{T_{SFN}}} < U_{\mathrm{T_{SC}}}$ and thus MBSFN should be preferred to SC-PTM. Furthermore, $U_{\mathrm{T_{SFN}}}$ decreases when increasing the size of the MBSFN area, which reinforces the interest of MBSFN compared to SC-PTM. Further simulations showed that the number of cases in which SC-PTM is more efficient increases for small MC areas. Conversely, MBSFN performs better in large MC areas.

# 5 CONCLUSION

In this paper, we have provided a model to calculate the SINR for a MC user in a mobile network transmitting in MBSFN, SC-PTM and Unicast modes. We assumed that the cells in the MBSFN area can decide to not participate in the MBSFN transmission if there are not any interested UE camped on them. Furthermore, we consider the case in which MC users are camped on cells outside the MBSFN area. Additionally, we develop a model to compare MBSFN and SC-PTM based on the SSE and the User Threshold.

Our results showed that to increase the SINR in MBSFN when having a high UE density we need to increase the BS density. Conversely, if the UE density is low, a higher SINR is provided by reducing the BS density. On the other hand, the SINR in SC-PTM decreases with the UE density and increases with the BS density. Additionally, the results in terms of SSE and user threshold showed that the dominant parameter is the UE density. If the UE density is high MBSFN is more efficient than SC-PTM. On the contrary, SC-PTM is more efficient than MBSFN for low UE densities. Furthermore, MBSFN performs better with large MBSFN areas

and MC areas which makes it more suitable for emergencies during massive events. The objective of future work is to make a comparison in terms of energy efficiency, particularly for standalone deployments in emergency situations where the public network is not available.

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