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MBSFN and SC-PTM as Solutions to Reduce Energy Consumption in Cellular Networks

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Abstract

Reducing mobile network and device energy consumption is one of the main objectives of the fifth and future sixth-generation (5G and 6G) cellular networks. This paper studies the Base Station (BS) and User Equipment (UE) energy consumption in scenarios where many users demand the same content and broadcast transmission might be used. We present analytical models to calculate the energy consumption in unicast, Multicast Broadcast Single Frequency Network (MBSFN), and Single-Cell Point-to-Multipoint (SC-PTM). Furthermore, we calculate the number of users per cell from which SC-PTM or MBSFN help to reduce BS and UE energy consumption compared to unicast.

Index Terms - MBSFN, SC-PTM, Broadcast, Unicast, Mobile Networks, Stochastic Geometry, Energy Consumption.

1 Introduction

Energy consumption is a great concern in many fields of study due to the economic and environmental cost of energy production. Specifically, mobile networks account for 1-2% of the world energy consumption [1]. Thus, one of the main requirements for the fifth generation (5G) of cellular networks is a 90% reduction in network energy usage [2]. Broadcast transmission is a promising solution to reduce energy consumption in scenarios where many users demand the same content as sportive events or group communications in mission critical scenarios. However, few works study the energy consumption of broadcast transmission compared to unicast transmission. In [3] and [4], we show that in situations where many users demand the same content, broadcast transmission allows to reduce bandwidth utilization compared to unicast. Our results motivated this study in which we compare broadcast and unicast in terms of Base Station (BS) and User Equipment (UE) energy consumption.

Multicast-Broadcast Single-Frequency-Network (MBSFN) and Single-Cell Point-to-Multipoint (SC-PTM) are the two broadcast technologies standardized by the Third Generation Partnership Project (3GPP). SC-PTM refers to broadcast transmission in only one cell. Users in the cell interested in the broadcast content receive the same information at the same bitrate. The bitrate is set based on the user with the lower Signal-to-Interference-plus-Noise Ratio (SINR) in the cell. This is different from unicast in which each terminal receives at a bitrate according to its SINR thanks to link adaptation techniques. However, in terms of interference, SC-PTM and unicast are similar because neighboring cells generate interference power. MBSFN transmission consists on a group of synchronized cells, called MBSFN area, that transmit the same information at the same time to the users demanding the broadcast content. The transmission bitrate aims to cover the users with the lowest SINR in the whole service area. With MBSFN interference is generated only by the cells outside the MBSFN area.

The problem we address in this paper is the switching between unicast and broadcast in order to reduce energy consumption. Energy consumption depends on many system parameters: bitrate, transmission time, transmission power, bandwidth, transmission mode, network deployment, among others. Providing a model that considers all these parameters is not an easy task. Authors in [5], proposed a scheduling algorithm to reduce UE energy consumption when receiving in MBSFN mode. They showed that MBSFN helps to reduce energy consumption on the UE compared to unicast. However, a model for SC-PTM and a BS energy consumption model are not provided.

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This study provides an analytical model to calculate the energy consumption on the UE side and the BS side in unicast, MBSFN and SC-PTM transmission modes. The model considers BS and UE distributed according to Poisson Point Processes (PPP). This allow us to use stochastic geometry theorems and previous results. Furthermore, we calculate the number of users per cell to switch from unicast to MBSFN or SC-PTM in order to reduce energy consumption. Afterwards, we compare the user threshold to reduce radio resource utilization [3], with the user threshold to reduce BS and UE energy consumption.

The remainder of this paper is structured as follows. Section II presents the research work that set the basis of our study and section III presents the energy consumption models. In section IV we present the analytical calculation of the user thresholds from which MBSFN and SC-PTM help to reduce energy consumption in the UE and BS side. Results are presented and analysed in section V and conclusions are presented in section VI.

2 Related Work

2.1 Power Consumption Model

This section presents the UE and BS power consumption models used to calculate energy consumption.

2.1.1 User Equipment Model

In this study we consider the LTE UE power consumption model presented in [6]. According to this model the power consumed by a UE in downlink (DL) is calculated as

$$P_{\text{UE}} = P_{\text{con}} + P_{\text{Rx}} + P_{\text{RxRF}}(U_{\text{Rx}}) + P_{\text{RxBB}}(C_{\text{Rx}}), \quad (1)$$

where P_{con} is the average power consumption in Radio Resource Configuration (RRC) connected mode and P_{Rx} is the base power the UE signal-processing-chain consumes when active. The power consumed by the Radio Frequency (RF) parts, P_{RxRF} , is a function of the downlink power level in dBm, U_{Rx} , and it is given by

$$P_{\text{RxRF}}(U_{\text{Rx}}) = p_{0\text{RF}} + p_{1\text{RF}}U_{\text{Rx}}. \quad (2)$$

The power consumed by the Baseband (BB) parts, P_{RxBB} , is a function of the DL bitrate in Mbit/s, C_{Rx} , and it is calculated as

$$P_{\text{RxBB}}(C_{\text{Rx}}) = p_{0\text{BB}} + p_{1\text{BB}}C_{\text{Rx}}. \quad (3)$$

The values for P_{con} , P_{Rx} , $p_{0\text{RF}}$, $p_{1\text{RF}}$, $p_{0\text{BB}}$ and $p_{1\text{BB}}$ are constant and provided in [6]. Therefore, the UE power consumption depends on the DL power level (U_{Rx}) and the DL bitrate (C_{Rx}). In this study we use a fixed value for U_{Rx} , thus the UE consumed power can be expressed as

$$P_{\text{UE}} = K + p_{1\text{BB}}C_{\text{Rx}}, \quad (4)$$

where $K = P_{\text{con}} + P_{\text{Rx}} + P_{\text{RxRF}}(U_{\text{Rx}}) + p_{0\text{BB}}$.

2.1.2 Base Station Model

The Base Station power consumption is studied using the model presented in [7]. The model considers an LTE system with 10 MHz bandwidth and a BS maximum transmit power of 43 dBm. A BS antenna is served by a transceiver (TRX) that comprises: a power amplifier, an RF small-signal TRX module, a BB engine, a DC-DC power supply, an active cooling system and an AC-DC unit for connection to the electrical grid. Considering all these components, authors of [7] estimate the power consumption per TRX chain for LTE Macro Base Stations (P_{BS}).

2.2 SINR probability distribution

Some authors have developed analytical expressions to calculate the SINR probability distribution of users when receiving in unicast and MBSFN transmission modes using stochastic geometry. This section presents how to calculate the probability of coverage for unicast and MBSFN which is the SINR Complementary Cumulative Distribution Function (CCDF) such that $p_c(T) = \mathbb{P}[S > T]$, where S is the random variable (r.v.) representing the SINR and T is the SINR threshold.

2.2.1 Unicast

Authors in [8] propose an expression to calculate the probability of coverage in unicast (p_{cUC}) as follows

$$p_{\text{cUC}}(T) = \pi \lambda_{\text{BS}} \int_0^\infty e^{-\pi \lambda_{\text{BS}} v (1 + \rho(T, \alpha)) - T P_{\text{N}} v^{\alpha/2}} dv, \quad (5)$$

where

$$\rho(T, \alpha) = T^{2/\alpha} \int_{T^{-2/\alpha}}^\infty \frac{1}{1 + u^{\alpha/2}} du, \quad (6)$$

where $P_{\text{N}} = \frac{N}{P_{\text{tx}} k}$ is the normalized noise power. P_{tx} denotes the BS transmission power and N the noise power. They consider omnidirectional BS located according to a PPP of density λ_{BS} and the path loss model is based on Okumura-Hata-Cost231 with fading. The path loss exponent is denoted as α and the path loss factor as k . The received power is thus given by $P_{\text{tx}} k / r^\alpha$ where r is the distance between the transmitter and the receiver. Rayleigh fading is modeled as an exponential random variable (r.v.) with unit rate.

2.2.2 MBSFN

In the case of MBSFN, we proposed an expression in [4] to calculate the probability of coverage for a user located at any place inside an MBSFN area. This area is formed by the BS located inside a disk of radius R_s . The total considered area is a disk of radius R such that $R > R_s$. Let ξ be the ratio between the distance from the user to the center and the radius R_s of the MBSFN area as shown in Fig. 1 ($0 \leq \xi \leq 1$). Other parameters are similar to the unicast model. Therefore, the probability of coverage for a user receiving in MBSFN mode is calculated as

$$p_{\text{cSFN}}(T) = \frac{1}{2} + \frac{1}{\pi} \int_0^\infty \frac{1}{t} \text{Im}[\mathcal{L}_1(jtT) e^{-jtT P_{\text{N}}} \mathcal{L}_P(-jt)] dt, \quad (7)$$

where

$$\mathcal{L}_P(s) = \exp\left(-\lambda \int_0^{R_s} \int_0^{2\pi} \frac{sr}{s + D(r, \theta)^\alpha} d\theta dr\right), \quad (8)$$

$$\mathcal{L}_1(s) = \exp\left(-\lambda \int_{R_s}^R \int_0^{2\pi} \frac{sr}{s + D(r, \theta)^\alpha} d\theta dr\right), \quad (9)$$

and

$$D(r, \theta) = ((\xi R_s)^2 + r^2 - 2\xi R_s r \cos(\theta))^{\frac{1}{2}}. \quad (10)$$

2.3 User Threshold to switch from unicast to Broadcast

In this section, we use our analytical method [4] to calculate the number of users per cell to switch from unicast to broadcast (MBSFN or SC-PTM) in order to reduce radio resource utilization. The main steps are presented in the following for the sake of clarity.

2.3.1 Unicast to MBSFN

The user threshold to switch from unicast to MBSFN is calculated as

$$U_{\text{T}_{\text{SFN}}} = \frac{\Gamma_{\text{SFN}}}{\Gamma_{\text{UC}}}, \quad (11)$$

where Γ_{SFN} is the ratio between the system bandwidth (W) and bitrate (C) in MBSFN mode such that

$$\Gamma_{\text{SFN}} = \frac{W}{C} = \left[\frac{1}{\log_2(1 + S_{\text{mSFN}})} \right], \quad (12)$$

where S_{mSFN} is the minimum SINR to cover in MBSFN mode. It is determined based on the coverage requirement using (7). On the other hand, Γ_{UC} is the ratio between bandwidth and bitrate in unicast mode such that

$$\Gamma_{\text{UC}} = \frac{W}{C} = \mathbb{E} \left[\frac{1}{\log_2(1 + S)} \middle| S \geq S_{\text{mUC}} \right], \quad (13)$$

where S_{mUC} is the minimum SINR to cover in unicast mode. It is determined based on the coverage requirement using (5). The expected value is due to unicast link adaptation. It is solved as follows

$$\Gamma_{UC} = g(S_{M_{UC}})F(S_{M_{UC}}) - g(S_{m_{UC}})F(S_{m_{UC}}) - \int_{S_{m_{UC}}}^{S_{M_{UC}}} F(S) dg(S), \quad (14)$$

where $S_{M_{UC}}$ is the maximum SINR in unicast, $F(S) = 1 - p_{c_{UC}}(S)$ is the Cumulative Distribution Function (CDF) of the unicast SINR, $g(S) = \frac{1}{\log_2(1+S)}$ and

$$dg(S) = \frac{-\ln(2)}{(1+S)(\ln(S+1))^2} dS. \quad (15)$$

2.3.2 Unicast to SC-PTM

In the case of SC-PTM, the user threshold is calculated as

$$U_{T_{SC}} = \frac{\Gamma_{SC}}{\Gamma_{UC}}, \quad (16)$$

where

$$\Gamma_{SC} = \frac{W}{C} = \left[\frac{1}{\log_2(1+S_{m_{SC}})} \right]. \quad (17)$$

Since SC-PTM is broadcast transmission in one cell then, $S_{m_{SC}} = S_{m_{UC}}$.

3 Energy Consumption Model

Consider a service area in which the users are located following a PPP of density λ_{UE} . This service area is a disk smaller than the MBSFN area and centered on it, see Fig. 1. In MBSFN mode, the minimum SINR to cover ($S_{m_{MBSFN}}$) sets the transmission bitrate. This minimum SINR is usually perceived by users close to the border of the MBSFN area since they receive a high interference power. Therefore, we fix the radius of the service area as ξR_s and calculate the probability of coverage for a user at the border in order to determine the bitrate of the MBSFN transmission.

The UE power consumption depends on the transmission bitrate and the total energy consumption depends on the transmission time. Hereafter we present how to calculate these values and use them to obtain the energy consumption in unicast, MBSFN and SC-PTM.

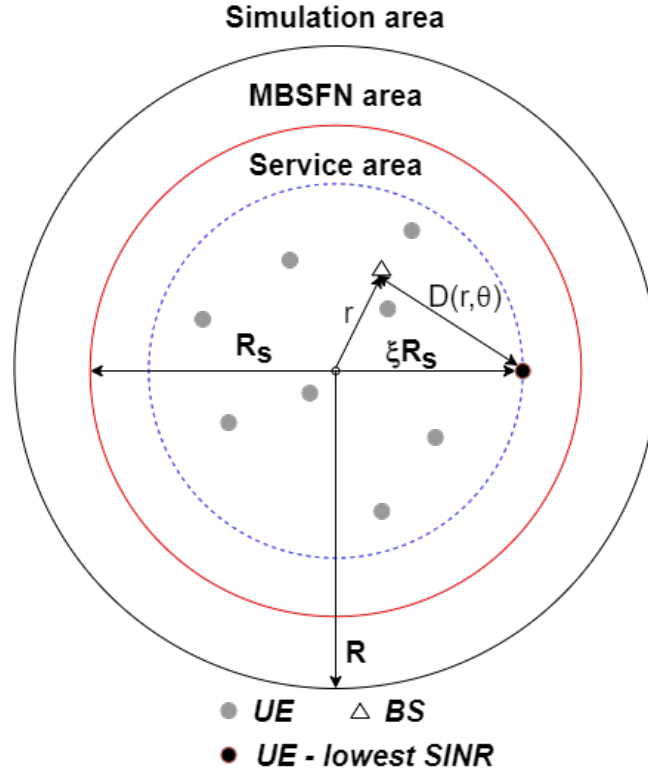


Figure 1: Model for the Energy Consumption in MBSFN mode

3.1 Energy Consumption in Unicast

The average downlink bitrate in unicast mode is calculated as

$$C_{\text{UC}} = W \mathbb{E} [\log_2(1 + S) | S \geq S_{\text{mUC}}]. \quad (18)$$

The expected value in (18) can be calculated as in (14) by using $g(S) = \log_2(1 + S)$ and, thus,

$$dg(S) = \frac{1}{S \ln(2) + \ln(2)} dS. \quad (19)$$

In unicast, the average transmission time [s/bit] is calculated as

$$t_{\text{UC}} = \mathbb{E} \left[\frac{1}{W \log_2(1 + S)} \middle| S \geq S_{\text{mUC}} \right] = \frac{\Gamma_{\text{UC}}}{W}, \quad (20)$$

Notice that $\mathbb{E} \left[\frac{1}{X} \right] \neq \frac{1}{\mathbb{E}[X]}$ and thus $t_{\text{UC}} \neq \frac{1}{C_{\text{UC}}}$. Now, the energy consumption for all the BS is calculated as

$$\begin{aligned} E_{\text{BSUC}} &= N_{\text{BSUC}} P_{\text{BS}} D_{\text{Tx}} t_{\text{UC}} \frac{N_{\text{u}}}{N_{\text{BSUC}}} \\ &= P_{\text{BS}} D_{\text{Tx}} t_{\text{UC}} N_{\text{u}}, \end{aligned} \quad (21)$$

where N_{BSUC} is the total number of BS that transmit in unicast mode, P_{BS} is the BS power consumption, D_{Tx} is the amount of data to be transmitted and $N_{\text{u}} = \lambda_{\text{UE}} \pi (\xi R_s)^2$ is the average number of users in the service area. Since BS in unicast do not transmit if there aren't any users camped on them, $N_{\text{BSUC}} = \min \{N_{\text{u}}, \lambda_{\text{BS}} \pi (\xi R_s)^2\}$. The factor $\frac{N_{\text{u}}}{N_{\text{BSUC}}}$ accounts for the fact that radio resources are shared in unicast. The more users per cell, the longer the time to transmit a certain data to all of them. Notice that E_{BSUC} does not depend on the BS density.

The energy consumption of all the UE is calculated as

$$\begin{aligned} E_{\text{UEUC}} &= N_{\text{u}} D_{\text{Tx}} t_{\text{UC}} \frac{N_{\text{u}}}{N_{\text{BSUC}}} \left(K + p_{1\text{BB}} C_{\text{UC}} \frac{N_{\text{BSUC}}}{N_{\text{u}}} \right) \\ &= N_{\text{u}}^2 \frac{D_{\text{Tx}} t_{\text{UC}} K}{N_{\text{BSUC}}} + N_{\text{u}} D_{\text{Tx}} t_{\text{UC}} p_{1\text{BB}} C_{\text{UC}}. \end{aligned} \quad (22)$$

Take into account that the UE power model considers the bitrate in Mbit/s. Furthermore, the average bitrate in unicast is multiplied by $\frac{N_{\text{BSUC}}}{N_{\text{u}}}$ because the capacity of each cell is divided equally among the users of the cell.

3.2 Energy Consumption in MBSFN

The downlink bitrate in MBSFN is calculated as

$$C_{\text{SFN}} = W [\log_2(1 + S_{\text{mSFN}})], \quad (23)$$

and the average transmission time is $t_{\text{SFN}} = \frac{1}{C_{\text{SFN}}} = \frac{\Gamma_{\text{SFN}}}{W}$. Then, the energy consumption for all the BS is calculated as

$$E_{\text{BS SFN}} = N_{\text{BS SFN}} P_{\text{BS}} D_{\text{Tx}} t_{\text{SFN}}, \quad (24)$$

where $N_{\text{BS SFN}} = \lambda_{\text{BS}} \pi R_s^2$, is the number of BS in the MBSFN area. Notice that $E_{\text{BS SFN}}$ does not depend on the UE density. On the other hand, the energy consumption for all the UEs is calculated as

$$E_{\text{UE SFN}} = N_{\text{u}} D_{\text{Tx}} t_{\text{SFN}} (K + p_{1\text{BB}} C_{\text{SFN}}). \quad (25)$$

3.3 Energy Consumption in SC-PTM

The downlink bitrate in SC-PTM is calculated as

$$C_{\text{SC}} = W [\log_2(1 + S_{\text{mSC}})], \quad (26)$$

and the average transmission time is $t_{\text{SC}} = \frac{1}{C_{\text{SC}}} = \frac{\Gamma_{\text{SC}}}{W}$. Notice that $S_{\text{mSC}} = S_{\text{mUC}}$. Then, the energy consumption for all the BS is calculated as

$$E_{\text{BS SC}} = N_{\text{BS SC}} P_{\text{BS}} D_{\text{Tx}} t_{\text{SC}}, \quad (27)$$

where $N_{\text{BS SC}} = N_{\text{BSUC}}$, is the number of BS that transmit in SC-PTM mode. On the other hand, the energy consumption for all the UE is calculated as

$$E_{\text{UE SC}} = N_{\text{u}} D_{\text{Tx}} t_{\text{SC}} (K + p_{1\text{BB}} C_{\text{SC}}). \quad (28)$$

4 User Threshold to Reduce Energy Consumption

This section provides an analytical model to calculate the number of users per cell to switch from unicast to broadcast (MBSFN or SC-PTM) to reduce BS and UE energy consumption.

4.1 Unicast to MBSFN

4.1.1 Base Stations Side

The comparison of BS energy consumption between unicast and MBSFN is as follows

$$P_{\text{BS}}D_{\text{Tx}}t_{\text{UC}}N_{\text{u}} > N_{\text{BS}_{\text{SFN}}}P_{\text{BS}}D_{\text{Tx}}t_{\text{SFN}}. \quad (29)$$

The user threshold, in number of user per cell in the MBSFN area, is the value of N_{u} that makes (29) an equality divided by $N_{\text{BS}_{\text{SFN}}}$, thus

$$U_{\text{SFN}_{\text{BS}}} = \frac{t_{\text{SFN}}}{t_{\text{UC}}} = \frac{\Gamma_{\text{SFN}}}{\Gamma_{\text{UC}}}, \quad (30)$$

which is the same value of user threshold when aiming to optimize radio resource utilization.

4.1.2 User Equipment Side

On the other hand, considering UE power consumption the comparison is as follows

$$E_{\text{UE}_{\text{UC}}} > E_{\text{UE}_{\text{SFN}}} \quad (31)$$

By combining (22) and (25), we get

$$aN_{\text{u}}^2 - bN_{\text{u}} \geq 0, \quad (32)$$

where

$$a = \frac{D_{\text{Tx}}t_{\text{UC}}K}{N_{\text{BS}_{\text{UC}}}}, \quad (33)$$

and

$$b = D_{\text{Tx}}(-t_{\text{UC}}p_{\text{1BB}}C_{\text{UC}} + t_{\text{SFN}}(K + p_{\text{1BB}}C_{\text{SFN}})). \quad (34)$$

Since $N_{\text{u}} \geq 0$, inequation (32) is verified if $N_{\text{u}} \geq b/a$. Thus, the user threshold in UE per MBSFN area cell for which the energy consumption on the UE side is reduced when transmitting in MBSFN mode is given by

$$U_{\text{SFN}_{\text{UE}}} = \frac{N_{\text{BS}_{\text{UC}}}}{N_{\text{BS}_{\text{SFN}}}} \left[\frac{t_{\text{SFN}}}{t_{\text{UC}}} - \frac{p_{\text{1BB}}}{K} \left(C_{\text{UC}} - \frac{1}{t_{\text{UC}}} \right) \right]. \quad (35)$$

As stated before, $N_{\text{BS}_{\text{UC}}} = \min \{N_{\text{u}}, \lambda_{\text{BS}}\pi(\xi R_s)^2\}$ therefore, $U_{\text{SFN}_{\text{UE}}}$ has two definitions depending on the values of λ_{UE} and λ_{BS} because

$$\frac{N_{\text{BS}_{\text{UC}}}}{N_{\text{BS}_{\text{SFN}}}} = \begin{cases} \xi^2 & \lambda_{\text{UE}} \geq \lambda_{\text{BS}} \\ \frac{\lambda_{\text{UE}}}{\lambda_{\text{BS}}} \xi^2 & \lambda_{\text{UE}} < \lambda_{\text{BS}} \end{cases} \quad (36)$$

Since $\frac{N_{\text{BS}_{\text{UC}}}}{N_{\text{BS}_{\text{SFN}}}} \leq 1$, K is always positive and $C_{\text{UC}} > \frac{1}{t_{\text{UC}}}$, because $\mathbb{E}[X] > \frac{1}{\mathbb{E}[\frac{1}{X}]}$, thus, we prove that $U_{\text{SFN}_{\text{UE}}} < U_{\text{SFN}_{\text{BS}}}$. This means that switching from unicast to MBSFN considering the user threshold in (11) and (30), helps to reduce radio resource utilization and energy consumption on the BS side and the UE side.

4.2 Unicast to SC-PTM

4.2.1 Base Stations Side

Following a similar procedure than for MBSFN, we obtain the number of users per cell from which the BS energy consumption in SC-PTM is lower than in unicast, as follows

$$U_{\text{SC}_{\text{BS}}} = \frac{t_{\text{SC}}}{t_{\text{UC}}} = \frac{\Gamma_{\text{SC}}}{\Gamma_{\text{UC}}}, \quad (37)$$

which is the same user threshold to reduce radio resource utilization.

Table 1: System parameters

Parameter	Value
Simulation area radius (R)	10 km
System Bandwidth (W)	10 MHz
Carrier Frequency (f_c)	700 MHz
BS Transmission Power (P_{tx})	43 dBm
Noise Power (N)	-95 dBm
Path Loss Exponent (α)	3.76
Path Loss Factor (k)	1.3804×10^{-12}
Target coverage probability	95%
BS power consumption (P_{BS})	225 W
UE RX power consumption (U_{Rx})	-40 dBm
P_{con}	1.53 W
P_{Rx}	0.42 W
p_{0RF}	-60.7×10^{-3}
p_{1RF}	-1.11×10^{-3}
p_{0BB}	-26.6×10^{-3}
p_{1BB}	2.89×10^{-3}

4.2.2 User Equipment Side

Furthermore, the number of users per cell from which the UE energy consumption is lower in SC-PTM than in unicast is calculated as

$$U_{SC_{UE}} = \frac{t_{SC}}{t_{UC}} - \frac{p_{1BB}}{K} \left(C_{UC} - \frac{1}{t_{UC}} \right). \quad (38)$$

This proves that $U_{SC_{UE}} < U_{SC_{BS}}$. However, the difference between $U_{SC_{BS}}$ and $U_{SC_{UE}}$ is negligible because p_{1BB} is of the order of 10^{-3} .

5 Results and Discussion

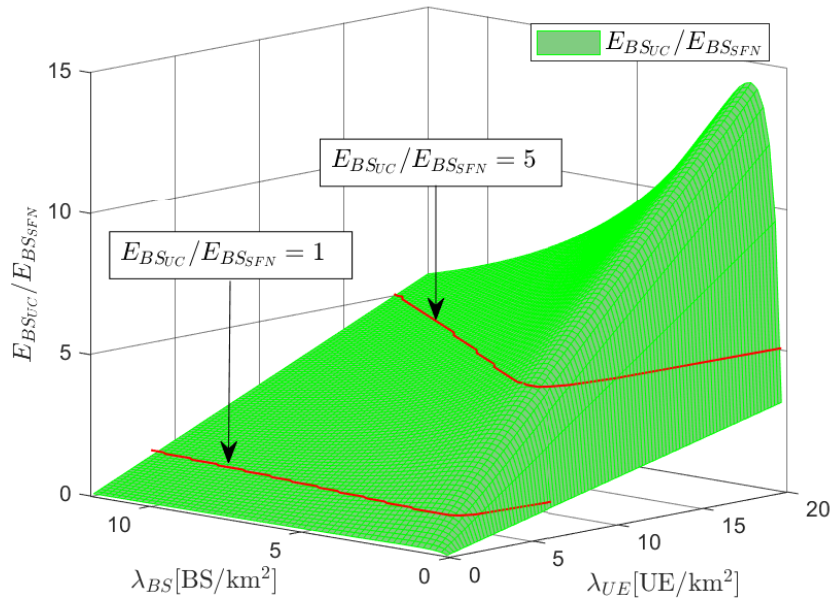


Figure 2: Ratio between the Base Station Energy Consumption in unicast and MBSFN modes for different λ_{BS} and λ_{UE} values, considering $R_s = 2.5$ km and $\xi = 0.7071$.

Figure 2 presents the ratio between the BS energy consumption in unicast mode (E_{BSUC}) and MBSFN mode

($E_{BS_{SFN}}$). We consider an MBSFN area of 19.6 km^2 ($R_s = 2.5 \text{ km}$) and a service area of 9.8 km^2 ($\xi = 0.7071$). With MBSFN transmission the BSs consume less energy than in unicast mode when the user density is higher than 3.8 UE/km^2 for $\lambda_{BS} = 12 \text{ BS/km}^2$. For lower BS densities, until 1.2 BS/km^2 , the value of λ_{UE} that makes $\frac{E_{BS_{UC}}}{E_{BS_{SFN}}} = 1$ decreases. However, if $\lambda_{BS} < 1.2 \text{ BS/km}^2$ more users are necessary for MBSFN to be more efficient. In this scenario, $\lambda_{BS} = 1.2 \text{ BS/km}^2$ minimizes the BS energy consumption in MBSFN mode for all UE densities. Additionally, observe that the BS energy ratio increases with the user density, e.g., with $\lambda_{BS} = 4 \text{ BS/km}^2$ and $\lambda_{UE} = 10 \text{ UE/km}^2$ the BSs consume 5 times more energy in unicast mode than in MBSFN mode.

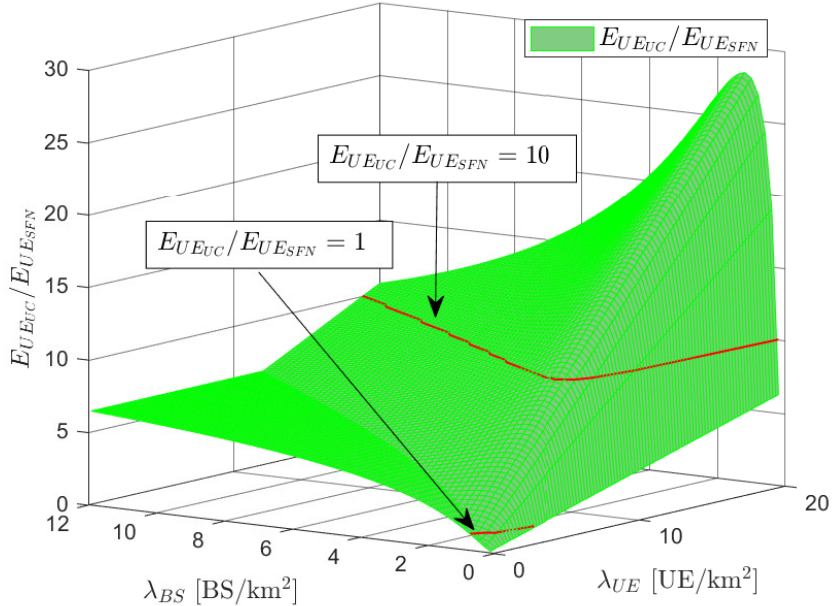


Figure 3: Ratio between the User Equipment Energy Consumption in unicast and MBSFN modes for different λ_{BS} and λ_{UE} values, considering $R_s = 2.5 \text{ km}$ and $\xi = 0.7071$.

The ratio between UE energy consumption in unicast mode ($E_{UE_{UC}}$) and MBSFN mode ($E_{UE_{SFN}}$) is presented in Fig. 3. Only when $\lambda_{BS} < 0.8 \text{ BS/km}^2$ and $\lambda_{UE} < 3.4 \text{ UE/km}^2$ the UE energy consumption is lower in unicast than in MBSFN. Apart from that, we see that in most cases the UEs energy consumption is lower when receiving in MBSFN than in unicast. This is because the UEs perceive a higher SINR in MBSFN mode due to a reduced interference and therefore, they receive at a higher bitrate and transmission is faster. In Fig. 3 we appreciate one surface when $\lambda_{UE} \geq \lambda_{BS}$ and other when $\lambda_{UE} < \lambda_{BS}$, this is due to the definition of $N_{BS_{UC}}$. In average there is one or less users per BS, the UE energy consumption in unicast is constant for a given λ_{BS} , however if there is more than one user per BS, the UE energy consumption increases due to the resource sharing in unicast. Similarly with the BS energy consumption, $\lambda_{BS} = 1.2 \text{ BS/km}^2$ minimizes UE energy consumption in MBSFN mode for all UE densities and the UE energy consumption ratio increases with λ_{UE} when $\lambda_{UE} \geq \lambda_{BS}$. As an example, if $\lambda_{BS} = 4 \text{ BS/km}^2$ and $\lambda_{UE} = 10 \text{ UE/km}^2$ the UEs consume 10 times more energy in unicast mode than in MBSFN mode.

Figure 4 presents the ratio between the BS energy consumption in unicast mode ($E_{BS_{UC}}$) and SC-PTM mode ($E_{BS_{SC}}$). First notice that the axis for λ_{BS} and λ_{UE} are inverted with respect to Fig. 2 and Fig. 3. We see that in most cases BSs consume more energy in SC-PTM mode than in unicast mode. However, the BSs consume less energy when transmitting in SC-PTM mode when λ_{BS} is low. This is because in unicast the BS energy consumption does not depend on the BS density, the more BS the lower the number of user in each BS and therefore, the transmission is faster. However, in SC-PTM mode, BSs energy consumption increases linearly with the BS density. On the other hand, the BS energy consumption in unicast increases with λ_{UE} while $E_{BS_{SC}}$ does not depend on the UE density. This is why the energy ratio increases with λ_{UE} . If we consider $\lambda_{BS} = 2 \text{ BS/km}^2$, SC-PTM helps to reduce BS energy consumption only if $\lambda_{UE} > 17.6 \text{ UE/km}^2$.

The user thresholds to switch from unicast to MBSFN or SC-PTM in order to reduce energy consumption in the BSs or UEs are presented in Fig. 5. We consider $\lambda_{BS} = 4 \text{ BS/km}^2$ and MBSFN areas ranging from 3.1 km^2 ($R_s = 1 \text{ km}$) up to 19.6 km^2 ($R_s = 2.5 \text{ km}$). The service areas have half the size ($\xi = 0.7071$) and 80% the size ($\xi = 0.9$) of the MBSFN area. First, notice that $U_{SC_{BS}}$ and $U_{SC_{UE}}$ are equal to 8.7 UE/cell . These values do not depend on λ_{UE} or λ_{BS} . On the other hand, the user thresholds for MBSFN decrease with the MBSFN area size. The bigger the MBSFN area, the higher the SINR and therefore the lower the energy consumption in

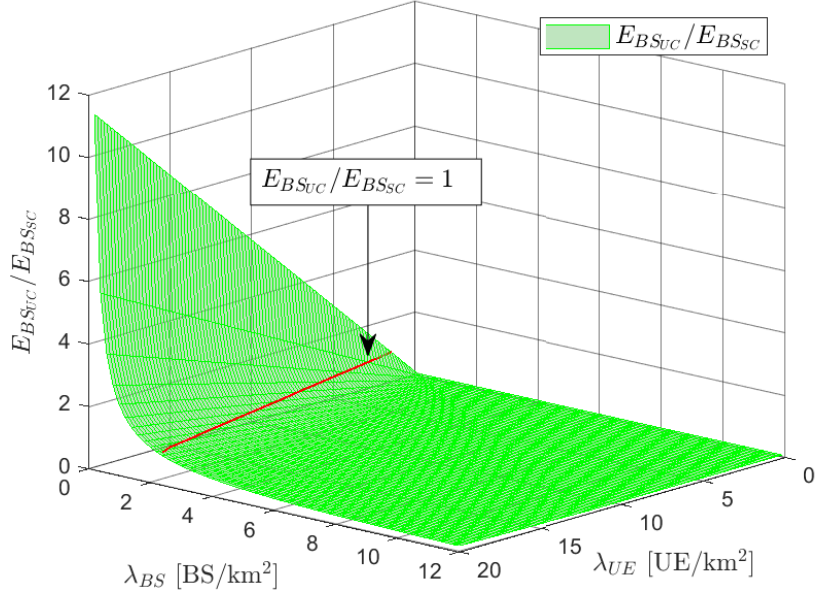


Figure 4: Ratio between the Base Station Consumption in unicast and SC-PTM modes for different λ_{BS} and λ_{UE} values.

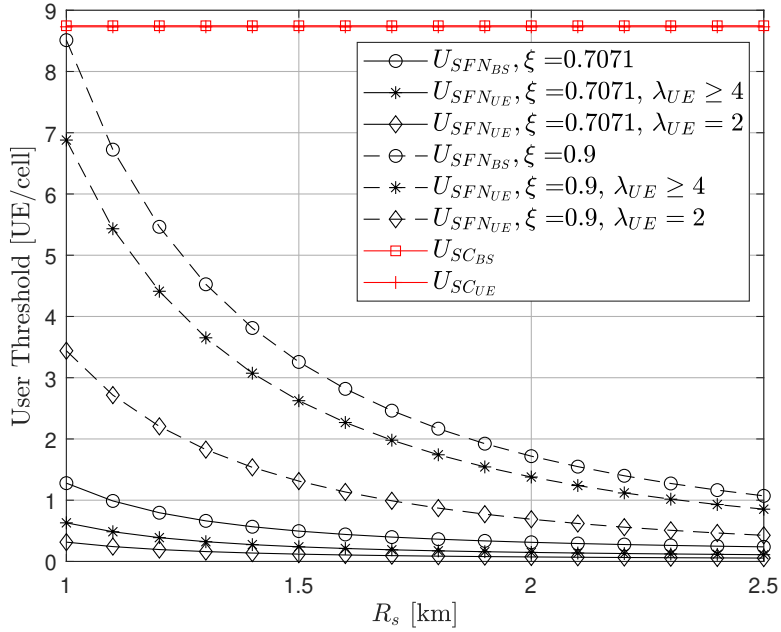


Figure 5: User Threshold to switch from unicast to MBSFN or SC-PTM in order to reduce Energy Consumption on the Base Stations or User Equipments for different service area and MBSFN area configurations and user densities.

MBSFN. We see as well that the size of the Service area has an important impact on the user threshold, e.g., if $R_s = 1$ km, U_{SFNBs} increases from 1.27 UE/cell to 8.5 UE/cell when increasing ξ from 0.7071 to 0.9. This is due to the higher interference perceived by the users at the border of the service area. Now, when $\lambda_{UE} \geq \lambda_{BS}$, the difference between U_{SFNBs} and U_{SFNUe} is lower than 2 UE/cell in all cases. However, if $\lambda_{UE} \geq \lambda_{BS}$, U_{SFNUe} can be significantly lower than U_{SFNBs} . For example, if $R_s = 1$ km, $U_{SFNUe} = 3.44$ UE/cell while $U_{SFNBs} = 8.5$ UE/cell.

6 CONCLUSION

This paper presents an analytical model to calculate the energy consumption in the Base Stations and User Equipment when transmitting using unicast, SC-PTM and MBSFN mode. Furthermore, we developed expressions to calculate the number of users per cell from which SC-PTM or MBSFN reduce BS or UE energy consumption with respect to unicast.

We proved that the user threshold to reduce BS energy consumption are the same as the user threshold to reduce radio resource utilization, in both SC-PTM and MBSFN mode. We also proved that the user threshold to reduce UE energy consumption is lower than the user threshold to reduce BS energy consumption, in particular for MBSFN. The results show that MBSFN is a better solution than SC-PTM to reduce energy consumption in most cases. As future work we intend to explore machine learning techniques and data from real cellular network deployments to determine the scenarios in which broadcast transmission mode can reduce energy consumption.

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