Optimal Density of Base Stations in Dense Networks From the Point of View of Energy Efficiency

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Abstract – To cope with the traffic explosion and the demand for new services in cellular networks, broadcast transmission is emerging as a promising approach for the fifth generation (5G). One such approach, called Multicast Broadcast Single Frequency Network (MBSFN), consists of synchronized transmissions between multiple base stations (BSs), which reduces intercell interference, improves reliability and coverage, and provides an energy-efficient solution. In this article, we investigate the ability of MBSFN to reduce intercell interference and improve energy efficiency compared to the conventional unicast-based network, even when the latter is applied with beamforming. We also investigate the optimal BS density and the optimal MBSFN area size, defined by the threshold values for which broadcast mode becomes more efficient than unicast mode (with or without beamforming), with regard to energy efficiency. Furthermore, we examine the effect of various system parameters on the energy efficiency gain that broadcast mode can provide compared to unicast mode, in a scenario where the BSs are randomly distributed with a high density and transmit the same content in downlink.

1. Introduction

The data traffic generated by cellular networks has increased dramatically in recent years; thus future cellular networks must be designed to meet the increasing demand for data-intensive services such as multimedia services [1–3]. To achieve this goal, we plan to use several fifth-generation (5G) techniques, including broadcast mode transmission with intercell cooperation, network modeling following the Poisson point process (PPP), massive deployment of base stations (BSs), and the use of unicast beamforming.

In the context of cellular networks, data transmission can be performed in unicast or broadcast mode [4–7]. Although unicast mode allows for adaptive transmission on both the technical and the content level, it requires transmitting the same content as many times as the number of users requesting it. Due to spectrum scarcity, the number of users served is limited and becomes smaller and smaller when the service requires a high bit rate, such as video streaming [6]. To overcome this challenge, broadcast mode is considered an attractive solution for efficient resource utilization when the same content is transmitted to multiple users simultaneously [4–7].

Furthermore, the topology of a network, specifically the density and location of BSs, has a significant impact on its performance, which is especially true in the context of high-density wireless networks such as 5G. Thus, two widely recognized approaches exist for cellular network design: the hexagonal model and the PPP model [4, 7]. Hexagonal cells have been commonly used to model and control the deployment of cellular networks while ensuring seamless and nonoverlapping coverage. Nevertheless, the hexagonal model lacks the accuracy to describe a real network, especially in areas where the density of users varies considerably. In contrast, modeling the network according to the PPP model allows for a more realistic representation in which the BSs are randomly distributed. This approach has the advantage of taking into account the impact of the density of BSs that is ignored in the hexagonal model. However, it is widely recognized that although deploying high-density BS networks is a promising solution for future 5G and 6G networks [8–10], it also comes with issues of interference management and energy consumption [11, 12]. Moreover, due to the stochastic nature of the network model (where BSs are randomly distributed according to PPP), the interference impact becomes more significant, leading to a reduction in the signal-to-interference-and-noise ratio (SINR).

In this article, we aim to analyze in different scenarios the ability of broadcast mode to reduce interference and improve energy efficiency compared to unicast mode. Unlike previous works [13, 14] where a hexagonal model was used to model the network, in this study we use the PPP to model the distribution of BSs. In addition, this study takes into account intercellular interference, which has been neglected in previous works [13–15]. Moreover, unlike previous works [5, 7, 16] that considered only single-cell broadcast, our work focuses on multicell broadcast via Multicast Broadcast Single Frequency Network (MBSFN). This work is an extension of [4], which evaluates and compares the SINR performance of unicast and broadcast modes in a scenario where all BSs transmit the same content. Furthermore, in this article we consider two cases of study related to the broadcast mode: in the first case, all BSs transmit, whereas in the second case, only a certain number of BSs transmit and thus form a MBSFN area, with the remaining BSs (located outside the MBSFN area) treated as interference sources. The main objective of this article is to determine the optimal density of BSs and the optimal size of the MBSFN area, defined by the thresholds beyond which broadcast mode exceeds

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unicast mode in terms of energy efficiency. Extensive simulations are performed to find the set of parameters to maximize energy efficiency. These results are intended to serve as a guide for network densification.

2. System Model and Performance Metrics

The study area is a square in which we use the PPP approach to model the distribution of BSs. In this approach, the location of the BSs is modeled by a single parameter that represents the density (expressed in terms of BS/km^2 in the rest of this article). Furthermore, the BSs are assumed to have three sectors (each with a width of 120°), with matched antennas capable of beamforming in unicast mode. It is assumed that all BSs transmit the same orthogonal frequency division multiplexing (OFDM) signal at the same transmit power P_{tx} and use the same carrier frequency f_{c} and frequency band B.

We consider a propagation model that includes path loss, fading, and shadowing, referring to the model proposed by the Third Generation Partnership Project (3GPP) [17]. We consider the fading factor (denoted h) as an exponentially distributed random variable with unit rate. Also, we model shadowing with the parameter e^{χ}, where χ is a random variable that follows a normal distribution with mean zero and variance σ^2. Considering now a user located at a distance $r_{g,i}$ from some BS i, we can therefore express the received signal power as:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} \kappa r_{g,i}^{-\alpha} e^{\chi} h_i G(\theta) \tag{1}$$

where κ is the attenuation coefficient, α is the path loss exponent, and $G(\theta)$ is the antenna gain in the direction θ calculated according to [17].

In the following, we examine unicast and broadcast downlink SINR and energy efficiency for a typical user placed at the center of the study area. The SINR is defined in both modes as the ratio of the received power P_{r} to the sum of the interference power I_{r} and the noise power at the receiver P_{N}—that is, $\gamma = \frac{P_{\mathrm{r}}}{I_{\mathrm{r}}+P_{\mathrm{N}}}$.

In unicast mode (with and without beamforming), only the service BS (which is not necessarily the closest to the user) provides useful signal power; all other BSs in the study area generate interference [4]. Thus the received signal power P_{r} is calculated taking into account the serving BS. Regarding the interference power I_{r}, it is decomposed into two parts. The first part is related to the interference sectors of the tri-sector service BS. The second part is related to the other BSs belonging to the study area. Note that in the case of unicast transmission with beamforming, the SINR is calculated in the same way, but this time using a uniform linear network composed of a number of antennas per sector (denoted M) [4].

Let us now discuss how the energy efficiency is calculated when transmission is performed in unicast mode. According to Shannon's theorem, the capacity of a transmission can be calculated by $C = B\log_2(1+\gamma)$. The known strategy for transmitting a service consists of satisfying the condition $C = B\log_2(1+\gamma) \geq C_{\mathrm{req}}$ (where C_{req} is the capacity required to access the service). The energy efficiency is calculated in the best-known form as:

$$\mathrm{EE_{UC}} = \frac{B\log_2(1+\gamma)}{P_{\mathrm{tx}}} (b/s/W) \tag{2}$$

Therefore, to calculate the average energy efficiency in the case of a user served in unicast mode, for a number of BS locations, we average all capacity values starting from the minimum SINR γ^0_{UC} to the highest one as follows:

$$\overline{\mathrm{EE_{UC}}} = \frac{B}{P_{\mathrm{tx}}} \mathbb{E}\left[\log_2(1+\gamma_{\mathrm{UC}})|_{\gamma_{\mathrm{UC}} \geq \gamma^0_{\mathrm{UC}}}\right] \tag{3}$$

where γ^0_{UC} is the worst-case SINR computed in this article for two values of outage probability $p_0 = 5\%$ and 10%—that is, the minimum SINR among the 95% or 90% of users with the best channel conditions, respectively.

In the case of broadcast transmission via an MBSFN, several BSs transmit the same signal in intercell cooperation. Therefore, all the signals received from the BSs in the MBSFN area contribute not only to the useful power of the received signal but also to the interference power. Taking the example of a user in the MBSFN area located at a distance r_{s} from the serving BS and at a distance r_i from another BS BS$_i$ belonging to the same MBSFN area, the signal received from BS$_i$ arrives with a certain delay:

$$\Delta\tau = \frac{r_{\mathrm{s}} - r_i}{c} \tag{4}$$

where c is the speed of light. In this context, we can define a parameter δ_i as a function of this propagation delay $\Delta\tau$, which denotes the rate of received power considered useful [6]:

$$\delta_i = \begin{cases} 1, & 0 \leq \Delta\tau \leq T_{\mathrm{g}} \\ \left(\frac{T_{\mathrm{u}} - \Delta\tau + T_{\mathrm{g}}}{T_{\mathrm{u}}}\right), & T_{\mathrm{g}} < \Delta\tau \leq T_{\mathrm{f}} \\ 0, & \Delta\tau > T_{\mathrm{f}} \end{cases} \tag{5}$$

where T_{u} is the duration of the useful symbol, T_{g} is the duration of the inserted guard interval, and $T_{\mathrm{f}} = T_{\mathrm{g}} + T_{\mathrm{u}}$ is the total duration of the OFDM symbol.

Let us now consider an MBSFN area composed of a number of BSs (denoted N_{SFN}) located around the origin and participating in the synchronized transmission in broadcast mode. Therefore, we calculate the total power received by the user based on all N_{SFN} BSs where the weight of each received signal is the parameter δ_i. Following the same idea, the same BSs in the MBSFN network generate interference power from the delayed signals, when the signal delay time $\Delta\tau$ exceeds the guard interval T_{g} at the receiver. We also considered in this work the interference generated by the other BSs located outside the MBSFN area. On the other hand, broadcast transmission is usually programmed to guarantee access to the service to all users present in the study area. Furthermore, the channel capacity has a fixed and constant value for all users and is calculated in the worst-case to guarantee an SINR that allows the correct reception of the service:

$$C_{\mathrm{BC}}^{0} = B\log_2\left(1+\gamma_{\mathrm{BC}}^{0}\right) \tag{6}$$

where γ_{BC}^{0} is the worst-case broadcast-mode SINR among the 90% (or 95%) of users with the best channel conditions. Therefore, the broadcast mode energy efficiency is calculated as:

$$\mathrm{EE}_{\mathrm{BC}} = \frac{C_{\mathrm{BC}}^{0}}{P_{\mathrm{tx}}} = \frac{B\log_2\left(1+\gamma_{\mathrm{BC}}^{0}\right)}{P_{\mathrm{tx}}} \tag{7}$$

We now define the energy efficiency gain, for a number of BS locations distributed along the PPP, as the energy efficiency ratio between broadcast and unicast mode, as follows:

$$G_{\mathrm{BC}} = \frac{\mathrm{EE}_{\mathrm{BC}}}{\overline{\mathrm{EE}_{\mathrm{UC}}}} = \frac{\log_2\left(1+\gamma_{\mathrm{BC}}^{0}\right)}{\mathbb{E}\left[\log_2(1+\gamma_{\mathrm{UC}})|_{\gamma_{\mathrm{UC}}\geq\gamma_{\mathrm{UC}}^{0}}\right]} \tag{8}$$

To the best of our knowledge, studies conducted to analyze and evaluate the energy gain that intercell cooperation via MBSFN can provide compared to beamforming remain very limited, and this is especially true when it comes to finding the optimal density of BSs (randomly deployed according to the PPP) when transmitting the same content in unicast/broadcast mode. In this context, extensive numerical evaluations are performed in the following section to assess this energy gain and the optimal density under different system conditions.

3. Numerical Results

To compare the performance of unicast and broadcast modes, we generate 10^4 Monte Carlo simulations, where each one corresponds to a random distribution of BS locations. It should be noted that we assume that all BSs transmit in unicast and broadcast mode at the same power. The considered service area is a square 400 km on a side, where the BSs are distributed according to PPP of density λ (expressed in BS/km^2). In order to comply with the 3GPP standard, all BSs transmit at the same carrier frequency $f_c = 2$ GHz and the same system bandwidth $B = 5$ MHz [17]. In addition, the channel is modeled following [17] with $\sigma_{\mathrm{dB}} = 10$ dB, $\alpha = 3.76$, $\kappa = 0.0295$, and $P_{\mathrm{N}} = -98$ dBm. Furthermore, the function δ_i is computed with $T_g = 16.67$ µs and $T_u = 66.7$ µs.

The plots in Figure 1 show the effect of the number of beamforming antennas M (considered only in unicast mode) on the average SINR γ_{mean} and the worst-case SINR $\gamma_{\min}$ (calculated for a 10% outage probability), for two BS density values $\lambda = 0.25$ and $\lambda = 2.5$. We find that increasing M for beamforming with unicast mode provides a significant gain in terms of γ_{mean} and $\gamma_{\min}$ compared to the conventional unicast mode where $M = 1$. For example, increasing M from 1 to 16 when $\lambda = 2.5$, we notice that γ_{mean} increases from 6.1 dB to 26 dB. Let us now compare unicast and broadcast modes when $M = 1$ (without beamforming). We observe that increasing λ gives no significant improvement in unicast mode, and this is due to the increase in total interference power, which becomes comparable to the received useful power. On the other hand, we can observe a significant improvement in broadcast mode, which shows the ability of the MBSFN technique to effectively reduce the total interference. In summary, we confirm that broadcast mode is largely more efficient than unicast mode, even when using beamforming with 16 antennas per sector, and this becomes even more evident at higher densities, reinforcing the advantages of broadcast mode in the context of upcoming dense 5G and 6G networks.

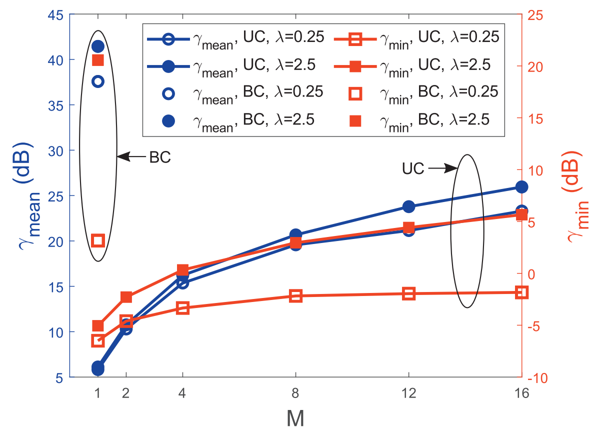

Figure 1. Average SINR γ_{mean} and worst-case SINR $\gamma_{\min}$ for a user served in unicast (UC) and broadcast (BC) modes as a function of M, for $P_{\mathrm{tx}} = 0.5$ W, $\lambda = 0.25$, and $\lambda = 2.5$.

In Figures 2 and 3, we evaluate the energy efficiency gain G_{EE} that broadcast mode can provide over unicast mode as a function of λ. We assume that all BSs (denoted N_{BS}) transmit in unicast mode. However, in broadcast mode, we consider two cases: all BSs

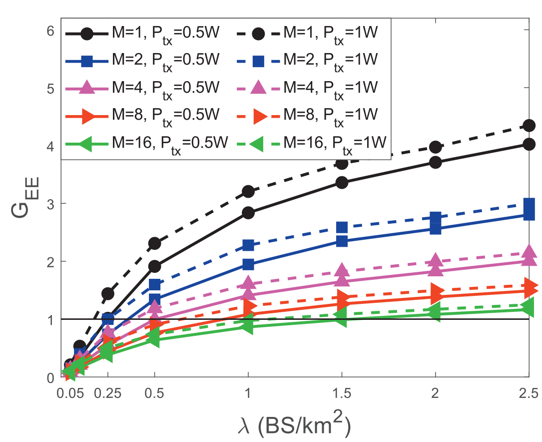

Figure 2. Energy efficiency gain G_{EE} as a function of λ, for different values of M, with $p_o = 10\%$, $P_{\mathrm{tx}} = 0.5$ W (solid line), and $P_{\mathrm{tx}} = 1$ W (dashed line).

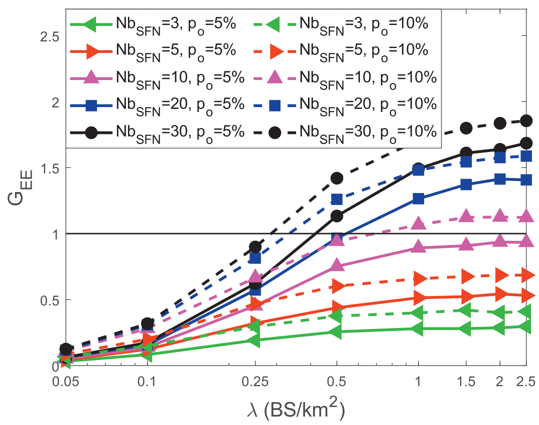

Figure 3. Energy efficiency gain $G_{\rm EE}$ as a function of λ, for different values of $N_{\rm SFN}$, with $P_{\rm tx} = 0.5$ W, $p_{\rm o} = 5\%$ (solid line), and $p_{\rm o} = 10\%$ (dashed line).

transmit (Figure 2) and only a number $N_{\rm SFN}$ of BSs (with $N_{\rm SFN} < N_{\rm BS}$) constituting the MBSFN area transmit (Figure 3). Note that in the latter case, all BSs outside the MBSFN area are treated as sources of interference. Special attention is given to finding the threshold values of the BS density λ and the size of the MBSFN area $N_{\rm SFN}$ beyond which broadcast mode becomes more energy efficient than unicast mode.

Figure 2 reveals that $G_{\rm EE}$ decreases as the number of antennas M increases. Indeed, this is consistent with Figure 1, where we showed that when we increase M, a significant performance gain is obtained in unicast mode with beamforming (increase in SINR, which leads to the increase in energy efficiency), which underlines the advantage of the latter over broadcast mode and thus explains the reduction of $G_{\rm EE}$. Furthermore, Figure 2 shows that $G_{\rm EE}$ increases when we increase $P_{\rm tx}$ from 0.5 W to 1 W. This is due to the fact that SINR continues to improve in broadcast mode, whereas in unicast mode the improvement in SINR is negligible (due to the increase in total interference power, which becomes comparable to the received useful power). Furthermore, we observe that $G_{\rm EE}$ increases as λ increases, confirming the importance of broadcast mode over unicast mode in reducing interference. We now examine the threshold value of the density λ at which broadcast mode becomes more energy efficient than unicast mode. We note that for $P_{\rm tx} = 0.5$ W (solid line), broadcast mode dominates unicast mode with $M = 1$ if $\lambda \geq 0.25$, with $M = 4$ if $\lambda \geq 0.5$, with $M = 8$ if $\lambda \geq 0.87$, and with $M = 16$ if $\lambda \geq 1.55$.

In Figure 3, we seek to evaluate $G_{\rm EE}$ in the scenario where only $N_{\rm SFN}$ BSs transmit in broadcast mode. This figure shows $G_{\rm EE}$ as a function of λ for $P_{\rm tx} = 0.5$ W, two values of outage probability $p_{\rm o} = 5\%$ (solid line) and $p_o = 10\%$ (dashed line), and different values of $N_{\rm SFN}$ between 2 BSs and 30 BSs. We conclude that $G_{\rm EE}$ increases with increasing λ, $N_{\rm SFN}$, or even $p_{\rm o}$, again confirming the advantages of broadcast mode via MBSFN over unicast mode. Looking at the effect of $N_{\rm SFN}$ on $G_{\rm EE}$, we find that when BSs are deployed with $\lambda = 2.5$, broadcast mode outperforms unicast mode in terms of energy efficiency when there are at least 10 BSs in the MBSFN area, and that this gain increases to approach 2 starting at $N_{\rm SFN} = 30$ BSs (with $p_{\rm o} = 10\%$). We also conclude that for $p_{\rm o} = 10\%$ (dashed line), broadcast mode dominates unicast mode when deployed with $N_{\rm SFN} = 30$ BSs and $\lambda \geq 0.3$, with $N_{\rm SFN} = 20$ BSs and $\lambda \geq 0.35$, or with $N_{\rm SFN} = 10$ BSs and $\lambda \geq 0.73$.

4. Conclusion

In this work, we sought to compare the energy efficiency of unicast (with and without beamforming) and broadcast (via MBSFN) modes under different conditions and constraints, and to find the set of parameters that maximizes this energy efficiency per user served. This study shows the benefits of broadcast transmission over unicast (even with beamforming) in reducing the interference generated by the BSs, which are randomly distributed and transmitting the same downlink content. It is shown that the energy efficiency gain that broadcast mode provides over unicast mode clearly increases with the increase in network density, BS transmission power, MBSFN area size, or outage probability. The results also indicate that it is possible to find an optimal MBSFN area size as well as an optimal density of BSs, beyond which broadcast mode becomes more energy efficient than unicast mode, which can be used to guide the topological design of future dense 5G and 6G networks.

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