Spectral Efficiency Optimization in Mass Transmission for Civil and Military Security

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Abstract – This article examines the optimization of spectral efficiency in the context of fifth-generation (5G) networks when massive cellular transmissions are performed by a group of base stations (BS) in emergency cases to ensure safety. Broadcast transmission is an important research topic to achieve this goal and is supported by related technology solution providers, such as the Third Generation Partnership Project. The main transmission modes of the LTE Evolved-Multimedia Broadcast/Multicast Service architecture are Single-Cell Point-to-Multipoint (SC-PTM), in which each BS independently broadcasts in its cell, and Multicast/Broadcast-Single Frequency Network (MB-SFN), in which a group of BS collaborating on the same frequency transmit synchronized signals. This article presents a study comparing these two broadcast modes: SC-PTM with the feature of combining it with beamforming technology and MB-SFN to determine the situations where one will be more efficient than the other. We demonstrate that there is no optimal mode that fits all situations, depending on the network configuration and system parameters. To do this, we aim to determine the optimal values of the number of antennas in SC-PTM mode and the width of the MB-SFN area for which one mode will surpass the other in terms of spectral efficiency. These results are intended to serve as a guide for massive transmissions in dense 5G networks to ensure civilian and military safety in small- and large-scale areas.

1. Introduction

The evolution of fifth-generation (5G) cellular networks aims to meet the growing and demanding needs of service providers and users, including higher data rates, massive connectivity, increased coverage probability, improved reliability, reduced latency, and improved spectral and energy efficiency [1–3]. Achieving these goals becomes increasingly complicated in public safety scenarios where high-density base stations (BS) downlink the same content as many times as the number of users. In this context, broadcast transmission, where the same critical content is delivered at once to everyone involved, has become essential to ensure smooth operations in both small areas (for police and military interventions) and large areas (to ensure the safety of a large public in entire cities). It is also widely recognized that broadcast transmission is a promising solution for the use of radio resources. This is because, unlike unicast transmission, which consists of sending customized content to each user separately, broadcast transmission consists of a single transmission to all users.

In the Third Generation Partnership Project (3GPP), the Multimedia Broadcast/Multicast Service (MBMS) was introduced as a solution to promote the multimedia service [4, 5]. With the evolved MBMS, the Multicast/Broadcast-Single Frequency Network (MB-SFN) broadcast mode was introduced in 3GPP versions 8 and 9 [6, 7]. The MB-SFN technique consists of sending the same information from a group of BS to all users on the same frequency and in a time-synchronized manner. Thus, the MB-SFN concept reduces inter-cell interference and improves the signal-to-interference-and-noise ratio (SINR), coverage, and spectral efficiency for users. The latest broadcast technique, defined in 3GPP Release 13, is Single-Cell Point-to-Multipoint (SC-PTM) which is a broadcast transmission performed by each BS independently [8, 9]. Unlike MB-SFN, SC-PTM has many similarities with unicast transmission, including transmission from a single BS without the need for synchronization with other BS, making it easy to implement. Another advantage of SC-PTM over MB-SFN is that the broadcast area can be decided dynamically for each BS and the network latency is shorter. However, the main limitation of SC-PTM is that it does not benefit from interference reduction like MB-SFN. For these reasons, each of these transmission modes has advantages and disadvantages that make it suitable for some scenarios and inefficient in others, so there is no optimal transmission mode in all cases. In this article, we attempt to answer the question of choosing the optimal mode, and to do so, we propose a comparative study of broadcast modes in different configurations and conditions.

This work builds on previous studies published in [10, 11]. The study [10] compares the unicast and MB-SFN modes in terms of SINR and concludes that MB-SFN mode always outperforms unicast mode regardless of BS density. However, this study is limited to the scenario where the MB-SFN zone covers the entire study area and does not consider SC-PTM mode. The second work [11] considers this time that a portion of the BS transmit in MB-SFN mode and shows that MB-SFN mode becomes more efficient than unicast mode from a certain value of the BS density and the number of BS in the MB-SFN area. In summary, our previous works [10, 11] did not take into account SC-PTM mode.

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This article aims to fill this gap by examining its effectiveness by combining it with beamforming technology and comparing it to MB-SFN mode. Particular attention is given to identifying the optimal values of the number of antennas in SC-PTM mode and the size of the MB-SFN zone for which one mode becomes more efficient than the other in terms of spectral efficiency.

To the best of the authors' knowledge, studies on spectral efficiency optimization in SC-PTM mode with beamforming and MB-SFN in the scenario where the BS (deployed randomly) transmit the same downlink content are still very limited in the literature. This is especially true when it comes to finding the optimal number of antennas in SC-PTM mode with beamforming and the optimal size of the MB-SFN area. Nevertheless, few works compare MB-SFN mode and SC-PTM mode without beamforming for public safety and critical applications [9, 12–14]. In contrast to these works, in our study, we consider that the BS are tri-sector (each with a 120° aperture) with antennas capable of using beamforming technology in SC-PTM mode and that the BS are distributed according to a Poisson Point Process (PPP) law instead of the regular hexagonal model. We also consider a wide range of BS density variations to account for the densification of future 5G and 6G networks while taking into account intra- and inter-cell interference.

2. Spectral Efficiency of the Proposed Solutions

The service area chosen is a square, and the propagation model considered is based on Okumura-Hata-Cost231, which includes path loss, shadowing, and fading effects according to the 3GPP reference model [15]. We consider the scenario where the tri-sector base stations are randomly distributed according to PPP with density λ (expressed in BS/km^2) and downlink orthogonal frequency division multiplexed signals at the same transmit power (P_{tx}) while using the same carrier frequency (f_c) and the same frequency band (B). In the following, we present the spectral efficiency of the SC-PTM with beamforming and MB-SFN modes for a user located at the center of the study area (which is considered as a reference for all users).

In SC-PTM mode, the serving BS is the one with the best SINR on the user side; it is not necessarily the closest to the user. Thus, the serving BS is the only one considered in the received power calculation, while all other BS in the study area are considered in the interference power calculation. The received signal power from the serving BS in SC-PTM mode with beamforming is calculated as follows:

$$P_{s,SC} = MP_{tx}\kappa r_s^{-\alpha} e^{\chi_c} h_s G\left(\theta_{s,t}\right) \quad (1)$$

where M is the number of antennas per sector, P_{tx} is the transmission power of the BS, κ is the attenuation coefficient, α is the path loss exponent, sub-index s denotes the serving BS, r_s is the distance between the user and his serving BS, h_s is the fading factor considered as an exponentially distributed random variable with unit rate, χ_c is the shadowing parameter considered as a random variable that follows a normal distribution of mean zero and variance σ^2, and $G(\theta)$ is the antenna gain in the θ direction measured from the antenna boresight axis as follows [15]:

$$G(\theta)[dB] = G_A - min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, G_{FB}\right] \quad (2)$$

where G_A is the antenna gain (expressed in dB) in the direction of the boresight, G_{FB} is the antenna front-to-back ratio (expressed in dB), $\theta_{3\mathrm{dB}}$ is the beam width at 3 dB, and $|\theta| \leq 180°$. Thus, the perceived SINR of a user served in SC-PTM mode with beamforming is calculated as follows:

$$\gamma_{SC} = \frac{P_{s,SC}}{I_{s,SC} + I_{i\in\Psi/i\neq s,SC} + P_N} \quad (3)$$

where $P_{s,\ SC}$ is the received signal power from the serving BS calculated according to (1), $I_{s,SC}$ is the interference power from the other two interference sectors of the serving BS, $I_{i\in\Psi/i\neq s,SC}$ is the interference power from the other BS belonging to the study area, and P_N is the noise power at the receiver. These powers are calculated as follows:

$$I_{s,SC} = P_{tx}\kappa r_s^{-\alpha} e^{\chi_c} h_x \sum_{j=1/j\neq t}^{3} A\left(\theta_{s,j}, \phi_{s,j}\right) \quad (4)$$

$$I_{i\in\Psi/i\neq s,SC} = P_{tx}\kappa e^{\chi_c} \sum_{i\in\Psi/i\neq s} r_i^{-\alpha} h_i \sum_{j=1}^{3} A\left(\theta_{i,j}, \phi_{i,j}\right) \quad (5)$$

$$P_N[dBm] = NF + 10log_{10}(KTB) \quad (6)$$

where sub-index t denotes the serving sector of the serving BS, sub-index j represents the interfering sectors of the serving BS ($j \neq t$), Ψ is the set of all BS distributed according to PPP, K is the Boltzmann constant, T is the temperature of the receiver system, NF is the receiver noise figure, B is the bandwidth, and $A(\theta, \phi)$ is the gain of the beamforming network for a sector in the θ-direction computed according to [16]:

$$A(\theta, \phi) = \begin{cases} \frac{sin^2\left[M\frac{\pi}{2}(sin(\phi)-sin(\theta)\right]}{Msin^2\left[\frac{\pi}{2}(sin(\phi)-sin(\theta)\right]} & ,\theta \neq \phi \\ MG(\theta) & ,\theta = \phi \end{cases} \quad (7)$$

where $G(\theta)$ is given by (2) and $-60 \leq \theta \leq 60$. The direction in which the beam is aimed is characterized by the steering angle ϕ, which is measured from the boresight of the antenna.

SC-PTM mode corresponds to a cell-wide broadcast transmission, meaning that each SC-PTM mode BS defines a target SINR target (γ_{SC}^0) to ensure adequate service reception by the target number of users. In our study, we aim for a 90% coverage probability of the users. As a result, γ_{SC}^0 is defined by the worst-case SINR among the 90% of users that receive the best channel conditions. Thus, the capacity is calculated based on Shannon's theorem, according to this coverage requirement, in order to guarantee the good reception of the service. This capacity expressed in bit/s is calculated by $C_{SC}^0 = Blog_2\left(1+\gamma_{SC}^0\right)$. Therefore, the spectral efficiency in SC-PTM mode is calculated by $ES_{SC} = \frac{C_{SC}^0}{B} = log_2\left(1+\gamma_{SC}^0\right)$.

In MB-SFN mode, we denote the number of BS in the MB-SFN area around the origin that contribute to the synchronized MB-SFN transmission as N_{SFN}. Therefore, the ratio of the number of BS in the MB-SFN area to the total number of BS (denoted N_{BS}) in the study area is $\rho = N_{SFN}/N_{BS}$ with $0 < \rho \le 1$ since $N_{SFN} \le N_{BS}$. Unlike [10], which considers all that BS in the study area to transmit in MB-SFN ($\rho = 1$), only the N_{SFN} BS located around the origin are considered in this study, implying that BS located outside the MB-SFN area generate interference. Thus, the SINR is calculated in the MB-SFN case by:

$$\gamma_{SFN} = \frac{P_{SFN}^{in}}{I_{SFN}^{in} + I_{SFN}^{out} + P_N} \tag{8}$$

where P_{SFN}^{in} is the total received power from the BS belonging to the MB-SFN zone and is calculated as a function of the parameter δ_i (see [10] for details on the calculation of δ_i), I_{SFN}^{in} is the interference power from the delayed signals in the MB-SFN zone, and I_{SFN}^{out} is the interference power related to the other BS located outside the MB-SFN zone. These powers are expressed as follows:

$$P_{SFN}^{in} = P_{tx} e^{\chi_c} \kappa \sum_{i=1}^{N_{SFN}} \delta_i r_i^{-\alpha} h_i \sum_{j=1}^{3} G\left(\theta_{i,j}\right) \tag{9}$$

$$I_{SFN}^{in} = P_{tx} e^{\chi_c} \kappa \sum_{i=1}^{N_{SFN}} \left(1-\delta_i\right) r_i^{-\alpha} h_i \sum_{j=1}^{3} G\left(\theta_{i,j}\right) \tag{10}$$

$$I_{SFN}^{out} = P_{tx} e^{\chi_c} \kappa \sum_{i \in \Psi / i > N_{SFN}} r_i^{-\alpha} h_i \sum_{j=1}^{3} G\left(\theta_{i,j}\right) \tag{11}$$

Following the same principle as in SC-PTM, the MB-SFN transmission is programmed to guarantee service access for a user with a target SINR γ_{SFN}^0 (worst case). Thus, the target capacity to be covered is calculated based on the γ_{SFN}^0 defined by the minimum SINR among the 90% of users with the best channel conditions as follows: $C_{SFN}^0 = Blog_2\left(1+\gamma_{SFN}^0\right)$. Therefore, the spectral efficiency for a number of BS locations in the MB-SFN area is calculated by $ES_{SFN} = \frac{C_{SFN}^0}{B} = log_2\left(1+\gamma_{SFN}^0\right)$

3. Numerical Results

The chosen service area is a square with a 20 km side where we place the BS randomly according to PPP of density λ. Note that to comply with the 3GPP standard, the main parameters were taken from [15]. We model the transmission channel with $f_c = 2$ GHz, $B = 5$ MHz, $\alpha = 3.76$, and $\kappa = 0.0295$. As such, we calculate the antenna gain $G(\theta)$ with $G_A = 15$ dBi, $G_{FB} = 20$ dBi, $\theta_{3dB} = 65°$, and the noise power P_N with $NF = 9$ dB and $T = 300$ K.

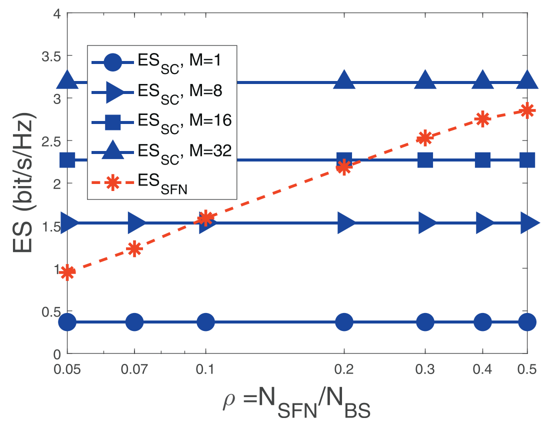

Figure 1. Spectral efficiency in SC-PTM (ES_{SC}) and MB-SFN (ES_{SFN}) modes as a function of ρ for $P_{tx} = 0.5$ W and $\lambda = 2.5$ BS/km^2.

In this section, we compare the performance of SC-PTM with beamforming and MB-SFN for efficiently transmitting the same content in case of a threat to public safety, taking into account the high density of BS in accordance with dense 5G networks. To do this, we perform 10^4 Monte Carlo simulations, each representing a new random distribution of BS locations. We then calculate the perceived SINR for each simulation and evaluate the spectral efficiency in SC-PTM mode with beamforming and in MB-SFN mode in the worst case. The spectral efficiency performance of SC-PTM with beamforming and MB-SFN modes is represented in Figure 1 as a function of ρ for different values of M. The transmission power (P_{tx}) is fixed at 0.5 W, and the BS density (λ) is 2.5 BS/km^2. We can observe that the spectral efficiency in MB-SFN mode increases with the increase of ρ, which reinforces the interest in this mode compared to SC-PTM. By closely examining the intersection between SC-PTM and MB-SFN, we can see that MB-SFN will be preferred to SC-PTM with $M = 8$ as soon as $\rho = 0.1$ (i.e., when more than 10% of the BS emit in MB-SFN) or preferred to SC-PTM with $M = 16$ as soon as $\rho = 0.2$ (i.e., when more than 20% of the BS emit in MB-SFN).

We note that the optimal values of M and ρ, represented in Figure 1, were determined using $P_{tx} = 0.5$ W and $\lambda = 2.5$ BS/km^2. It is important to keep in mind that these optimal values may vary if the BS transmission power (P_{tx}) changes or if the BS density (λ) is modified. To delve further into this topic, we examine the optimal values of M and ρ as a function of the transmission power P_{tx} (illustrated in Figure 2) and λ (illustrated in Figure 3).

In Figure 2, we evaluate the spectral efficiency of MB-SFN and SC-PTM modes as a function of P_{tx} for

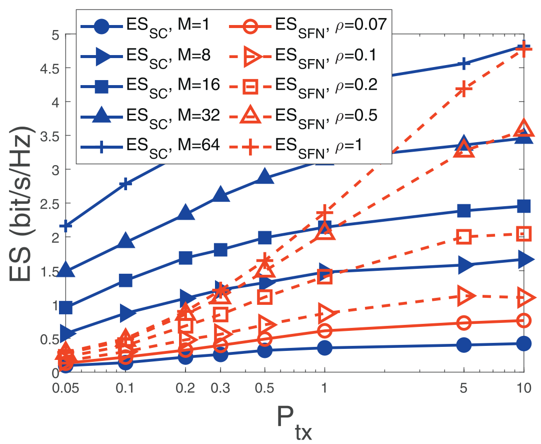

Figure 2. Spectral efficiency in SC-PTM (ES_{SC}) and MB-SFN (ES_{SFN}) modes as a function of P_{tx} W for $\lambda = 0.25$ BS/km^2.

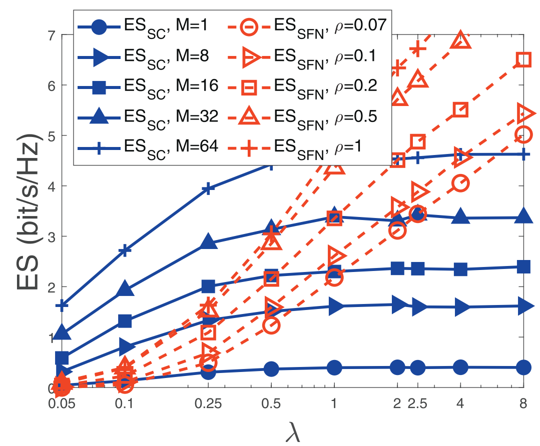

Figure 3. Spectral efficiency in SC-PTM (ES_{SC}) and MB-SFN (ES_{SFN}) modes as a function of λ BS/km^2 for $P_{tx} = 0.5$ W.

different values of the number of antennas ($M = 1$, 8, 16, 32, 64) and the size of the MB-SFN zone ($\rho = 0.07$, 0.1, 0.2, 0.5, 1). We observe that SC-PTM with a single antenna per sector ($M = 1$) offers the lowest spectral efficiency, while the proposed solutions, that is, SC-PTM with beamforming and MB-SFN, significantly improve the spectral efficiency over the entire P_{tx} range (due to the reduction of interference). We now examine the P_{tx} threshold value from which one of the two modes becomes more efficient than the other in terms of spectral efficiency. We observe that MB-SFN dominates SC-PTM with $M = 8$ as soon as $P_{tx} = 0.3$ W and $\rho = 1$ or as soon as $P_{tx} = 1$ W and $\rho = 0.2$. Furthermore, MB-SFN dominates SC-PTM with $M = 16$ as soon as $P_{tx} = 0.8$ W and $\rho = 1$ or as soon as $P_{tx} = 1$ W and $\rho = 0.5$. Additionally, MB-SFN dominates SC-PTM with $M = 32$ as soon as $P_{tx} = 2$ W and $\rho = 1$ or as soon as $P_{tx} = 6$ W and $\rho = 0.5$. Finally, MB-SFN dominates SC-PTM with $M = 64$ as soon as $P_{tx} = 10$ W and $\rho = 1$.

We now examine the threshold value of λ at which the SC-PTM with beamforming and MB-SFN modes become more or less performant compared to each other in terms of spectral efficiency. To do this, we vary λ from 0.05 BS/km^2 to 8 BS/km^2 in Figure 3 to address the challenges of network densification in the face of increasing interference. We find that MB-SFN provides superior spectral efficiency to SC-PTM with $M = 1$ as soon as $\lambda = 0.1$ and $\rho = 0.07$. Furthermore, MB-SFN dominates SC-PTM with $M = 8$ as soon as $\lambda = 0.2$ and $\rho = 0.5$, $\lambda = 0.3$ and $\rho = 0.2$, $\lambda = 0.5$ and $\rho = 0.1$, or $\lambda = 0.6$ and $\rho = 0.07$. Similarly, MB-SFN dominates SC-PTM with $M = 16$ as soon as $\lambda = 0.3$ and $\rho = 0.5$, $\lambda = 0.5$ and $\rho = 0.2$, $\lambda = 0.8$ and $\rho = 0.1$, or $\lambda = 1$ and $\rho = 0.07$. In the same way, MB-SFN dominates SC-PTM with $M = 32$ as soon as $\lambda = 0.5$ and $\rho = 1$, $\lambda = 1$ and $\rho = 0.2$, $\lambda = 1.8$ and $\rho = 0.1$, or $\lambda = 2.5$ and $\rho = 0.07$. Finally, MB-SFN dominates SC-PTM with $M = 64$ as soon as $\lambda = 0.9$ and $\rho = 1$, $\lambda = 1.1$ and $\rho = 0.5$, $\lambda = 2$ and $\rho = 0.2$, $\lambda = 4$ and $\rho = 0.1$, or $\lambda = 6$ and $\rho = 0.07$.

4. Conclusion

Optimizing spectral efficiency is one of the key challenges to be tackled for dense 5G networks, especially in a massive transmission scenario, in order to enhance civil and military security against potential threats. To achieve this goal, we proposed two solutions: SC-PTM mode with the particularity of combining it with beamforming and MB-SFN mode. We show that by varying the number of antennas in beamforming and the size of the MB-SFN zone, a crossover appears between the spectral efficiency curves of MB-SFN and SC-PTM, leading us to show that a mode cannot be optimal in all cases. We have therefore focused on finding optimal values of the number of antennas per sector and the size of the MB-SFN area, from which one mode becomes more efficient than the other in terms of spectral efficiency. We showed that these values are optimal for a certain network configuration and for certain system parameters and that new values can be obtained if the conditions are changed. This study is founded on network characteristics that align with actual deployments and endeavors to offer guidelines for large-scale transmission in upcoming 5G and 6G networks, thereby enhancing safety during emergency situations.

5. References

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