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Comparison of the transmission modes of 5G networks with a high density of base stations distributed according to Poisson Point Process

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Abstract

Mobile video traffic is growing rapidly with the advent of connected mobile devices such as smartphones and tablets, especially in the context of 5G networks. To cope with this traffic growth, cellular networks have undergone significant improvements in the recent years, especially via broadcast transmission when it comes to delivering mobile multimedia services to a large number of users. In this paper, we address the issue of performance evaluation of unicast and broadcast modes, when considering a network modeled with base stations distributed according to the PPP (Poisson Point Process) law instead of the traditional hexagonal model. The impact of varying the density of base stations is thus evaluated. The impact of using beamforming with the unicast mode is also evaluated using a certain number of antennas per sector of tri-sector base stations. The performance evaluation of unicast (even using beamforming) and broadcast modes is thus performed in terms of CDF (Cumulative Distribution Function) of the SINR (Signal to Interference & Noise Ratio), average SINR of the system, and the worst case SINR, taking into account the inter-cell interference.

1. Introduction

The network topology, i.e. density and placement of 5G base stations, has a high impact on its performance as it ascertains not only the strength of the received power signal but also the power level of the interferences.

The hexagonal lattice model has been commonly used to design and control the deployment of cellular networks and more specifically the macro cells layer [1][2]. Nevertheless, this traditional model is not appropriate for the small cells layer in terms of the density and distribution of base stations, especially in areas where the user density varies significantly [1]. In addition, the analysis of this model is relatively complex and not very tractable, especially when it comes to extracting performance metrics.

To overcome these limitations, stochastic geometry provides an alternative model and appropriate mathematical tools for network performance analysis (e.g. evaluation of coverage probability and system capacity) [3]. Furthermore, stochastic geometry models have the ability to represent near-realistic situations especially for small cells and dense urban environments and so they are gaining more acceptance for evaluating the performance of cellular networks. Following this approach, we consider that the position of the base stations follows Poisson Point Process (PPP) distribution, i.e., the BSs are randomly distributed over a 2D plane. In fact, the latter is modelled via a single parameter, representing the density of base stations denoted by λ, which is defined by the average value of the number of BSs in a certain service area.

In [3], the authors consider that the locations of the BSs follow the PPP distribution and propose to analytically address simplified expressions of performance metrics (such as coverage probability and capacity) of the network in broadcast transmission mode. However, the authors of [3] consider omni-directional antennas and do not take shadowing into account and consider broadcast transmission with a single transmitting cell.

Unlike previous works [3][4] that consider broadcast transmission with a single transmitter cell, our approach focuses on broadcast transmission with multiple broadcast transmitters via the Multicast Broadcast Single Frequency Network (MBSFN) technique. Moreover, unlike previous works that neglect the inter-cell interference in the case of multi-cell broadcast transmission [5][6], this paper takes into account the inter-cell interference as it represents a major factor affecting the quality of service of such a network. In this context, this work compares the expected performance of unicast and broadcast transmission modes by considering in the network modeling that the base stations are distributed according to PPP instead of the traditional hexagonal model. This work also addresses the issue of evaluating the effect of certain parameters (density of BSs, number of antennas per sector in unicast mode with beamforming) on the performance of unicast and broadcast modes. The performance evaluation is thus performed in terms of CDF of SINR, average SINR of the system, and worst case SINR.

2. System Model

We model the radio propagation with path loss, shadowing and fading effects by referring to the model proposed by

3rd Generation Partnership Project (3GPP) [7]. The study area considered is a square with a density λ (expressed in units of BS/km^2) defined by the number of distributed base stations according to PPP.

We assume that all base stations transmit OFDM signals at the same transmit power (P_{tx}) and use the same carrier frequency (f_c) as well as the same system bandwidth. Furthermore, we consider three-sector base stations with matched antennas capable of using unicast beamforming.

Considering a user located at a distance r_g from a certain base station, we can express the received power by the user as a function of path loss α, fading h, and shadowing e^{χ}, as follows:

$$P_{rx} = P_{tx}\frac{\kappa}{r_g^{\alpha}} h\, e^{\chi} \qquad (1)$$

where k is the attenuation coefficient and α is the path loss exponent; h is an exponentially distributed random variable (r.v.) with unit rate; χ is an r.v. that follows a normal distribution with zero mean and variance σ^2 (i.e., $\chi \sim N(0, \sigma^2)$).

The path loss in its linear form can be expressed as $L = \frac{r_g^{\alpha}}{\kappa}$ andwe can rewrite L in dB as $L\,[dB] = \alpha 10 log_{10}(r_g) - 10 log_{10}(\kappa)$. Therefore, the parameters α and κ can be calculated based on equation (2), expressed in dB, valid for carrier frequencies between 1400 MHz and 2600 MHz [7]:

$$L = 128.1 + 37.6 log_{10}(R) + 21 log_{10}\left(\frac{f_c}{2}\right), \qquad (2)$$

where R is the distance BS-user expressed in km (i.e. $R = \frac{r_g}{10^3}$), f_c is the carrier frequency expressed in GHz. In the remainder of the article, we fix f_c to 2 GHz, which gives $\alpha = 3.76$ and $\kappa = 0.0295$.

Shadowing is modeled as a log-normal r.v. $y \sim \exp(\chi)$ where $\chi \sim \mathrm{N}(0,\, \sigma^2)$. Shadowing is usually characterized in terms of the standard deviation of its dispersion σ_{dB} (en dB) $= \frac{10}{\sigma ln(10)}$. The random variable χ is composed of two parts: a correlated part (χ_c) accounting for obstacles close to the receiver and an uncorrelated part (χ_i) accounting for independent obstacles for each BS. Shadowing can thus be expressed as $y = e^{\chi_c + \chi_i}$ where $\chi = \chi_i + \chi_c$. The variance of the sum of these two independents normal r.v.'s can be expressed as $\sigma^2 = {\sigma_c}^2 + {\sigma_i}^2$. In the rest of the paper, we consider $\sigma_c^2 = \sigma_i^2 = \frac{\sigma^2}{2}$.

Thus, we can express the received signal power from BS i as follows:

$$P_{rx} = P_{tx}\frac{\kappa}{r_{g,i}^{\alpha}} e^{\chi_c} e^{\chi_i} h_i = P_{tx}\frac{\kappa}{{r_i}^{\alpha}} e^{\chi_c} h_i \qquad (3).$$

where $r_i = e^{-\frac{\chi_i}{\alpha}} r_{g,i}$ is the scaled distance $r_{g,i}$ which can be seen as a modification of the original base station location. According to [8], for a homogeneous (uniform) Poisson Point process (PPP) defined by the users located at distances $r_{g,i}$ and with density λ, if each point $r_{g,i}$ is transformed to r_i such that $r_i = e^{-\frac{\chi_i}{\alpha}} r_{g,i}$, the new PPP is also an homogeneous PPP of density $\lambda' = \lambda e^{2\frac{\sigma_i^2}{\alpha^2}}$.

3. Performance metrics

The SINR (Signal to Interference & Noise Ratio) is presented in this section, both in unicast (even with beamforming) and broadcast modes. We evaluate the performance of the transmission modes in terms of SINR for a user located at the center of the studied area. This user is considered as a typical user, i.e. considered as a reference for all users [9, Remark 1.6.6].

When the downlink transmission is performed in unicast mode, only the serving base station provides useful signal power and all other cells generate interference. The SINR for a user served in unicast mode can be expressed as follows:

$$\gamma_{UC} = \frac{P_{UC}}{I_{UC} + P_N} \qquad (4)$$

where P_{UC} is the received signal power, I_{UC} is the interference power of the received signal, and P_N is the noise power at the receiver.

The received signal power (P_{UC}) is calculated as follows:

$$P_{UC} = P_{tx}\frac{\kappa}{r_s^{\alpha}} e^{\chi_c} h_s G(\theta_{s,t}) \qquad (5).$$

where sub-index s denotes the service BS (which is not necessarily the closest to the user), sub-index t denotes the service sector of the service BS, r_s is the distance between the user and its service BS, and $G_{dB}(\theta)$ is the antenna gain in the θ direction [7].

The interference power received by a user in unicast mode is composed of two parts. The first part is related to the interference sectors of the service BS:

$$I_{UC,s} = P_{tx}\frac{\kappa}{r_s^{\alpha}} e^{\chi_c} h_s \sum\nolimits_{j=1/j\neq t}^{3} G(\theta_{s,j}) \qquad (6).$$

where j represents the sub-index of the interference sectors of the serving BS ($j \neq t$).

The second part of the interference power is related to the other BSs within the area of study:

$$I_{UC,i\in\psi/i\neq s} = P_{tx}\kappa e^{\chi_c} \sum\nolimits_{i\in\psi/i\neq s} {r_i}^{-\alpha} h_i \sum\nolimits_{j=1}^{3} (\theta_{i,j}) \qquad (7).$$

where ψ is the set of all base stations distributed in the area of study following PPP. Consequently, the SINR in unicast mode can be expressed as $\gamma_{UC} = \frac{P_{UC}}{I_{UC,s} + I_{UC,i\in\psi/i\neq s} + P_N}$.

For the unicast mode with beamforming, we use a uniform linear array (ULA) consisting of M transmit antennas per sector of three-sector base stations. Thus, the SINR is expressed as $\gamma_{UC}^{Beamf} = \frac{P_{UC}^{Beamf}}{I_{UC,s}^{Beamf} + I_{UC,i\in\psi/i\neq s}^{Beamf} + P_N}$ with

$$P_{UC}^{Beamf} = MP_{tx}\frac{\kappa}{r_s^{\alpha}}e^{\chi_c}\, h_s\, G\left(\theta_{s,t}\right) \quad (8).$$

$$I_{UC,s}^{Beamf} = P_{tx}\frac{\kappa}{r_s^{\alpha}}e^{\chi_c}h_s \sum_{j=1/j\neq t}^{3} A\left(\theta_{s,j}\right)$$

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

where $A(\theta)$ is the array gain for one sector in the direction θ [10].

We now present the case of broadcast transmission. In this work, we consider the simultaneous transmission technique MBSFN (Multicast Broadcast Single Frequency Network) which was introduced to support MBMS (Multimedia Broadcast Multicast Services) transmissions in LTE networks. In MBSFN, the same time-synchronized content is transmitted simultaneously and on the same frequency from a set of base stations (BSs). Considering a single frequency network composed of a number of BSs N_{SFN}, we can express the total power P_{BC} received by a user located at the origin of the plane as follows:

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

where N_{SFN} denotes the number of cells taking part in the MBSFN transmission, δ_i is the weight function of the useful portion of a received MBSFN signal [10].

Following the same idea, the same transmitters in the SFN generate interference power from delayed signals:

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

In the case of MBSFN transmission, there is another type of interference, related to other transmitters outside the SFN area:

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

4. Simulation results

The service area is chosen to be a square of side equal to 400 km, we locate the base stations following a PPP with a certain density λ. In this section we compare the expected performance of unicast and broadcast modes, considering that all base stations transmit at the same power P_{tx} = 0.5W and on the same carrier frequency f_c = 2 GHz, as well as in the same system bandwidth $\omega = 5\ MHz$. We model the transmission channel with $\sigma_{dB} = 10\ dB$, $\rho = 0.5$, $\alpha = 3.76$, $\kappa = 0.0295$. Note that in order to be 3GPP compliant, the main parameters have been taken from [7].

The first evaluation focuses on the location of the BSs. To do so, we generate 10^4 Monte Carlo simulations where each one corresponds to a new random distribution of the BSs locations. Then, for each simulation, we compute the SINR for a user located at the origin of the plane. Figure 1 shows the CDF of SINR in unicast and broadcast mode for different values of λ. The results in this figure show that the location of the base stations has a significant effect on the reception quality. This is explained by the variation margin of SINR which varies between a minimum value (less than -15 dB) and a maximum value (close to 16 dB in unicast mode and higher than 40 dB in broadcast mode).

To evaluate the effect of the BS density, we consider in Figure 1 different values of λ to describe the case where the user is more or less distant from its serving BS. Figure 1 shows that the unicast SINR improves with increasing λ, until there is no noticeable performance gain beyond λ = 0.25 BS/km^2. Indeed, when increasing λ, the user becomes close to its serving BS but also to other BSs belonging to the area of study, which induces interference, thus limiting the SINR in unicast mode. On the other hand, when the transmission is performed in broadcast mode, the SINR keeps on increasing even beyond λ = 0.25 BS/km^2. This shows the advantage of the SFN technique in reducing interference, especially at high base station density.

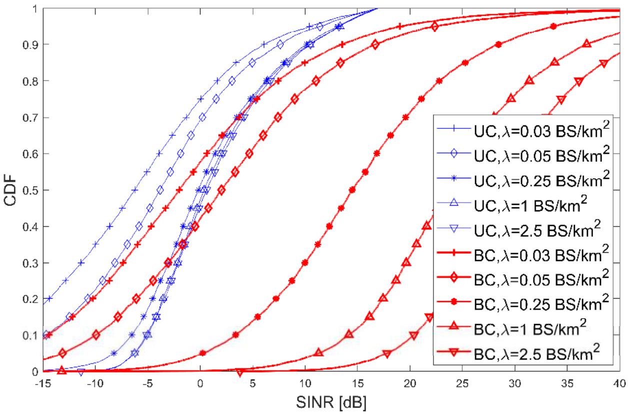

Figure 1. CDF of the SINR for a user served in unicast (UC) and broadcast (BC) modes, for different values of λ, with $\boldsymbol{P_{tx}}$ = 0.5W.

We are now interested in improving the performance of unicast transmission beyond the limit reached at λ = 0.25 BS/km². To do so, we consider the beamforming technique with unicast mode using M antennas per sector of tri-sector BSs. Note that the previous simulations are related to a single antenna per sector of tri-sector BS. We now study the effect of using multiple antennas on the average system SINR (Figure 2a) and the worst case SINR (Figure 2b). The average system SINR is the average of the SINRs obtained from Monte Carlo simulations corresponding to different random distributions of the BSs locations. The worst-case SINR is the minimum SINR computed for a 10% failure probability, i.e., the minimum SINR of 90% of users accessing the service.

Now let us analyse the effect of the number of antennas per sector M of the tri-sector BSs. The results in Figures 2a and 2b show a significant improvement in the average SINR and the worst case SINR, when increasing M from 1 to 16 (in unicast mode with beamforming). For example, looking at the UC curves for M=1 and M=16 at high λ, we see that we go from 6.11 dB to 25.95 dB in terms of the average SINR, while in terms of the minimum SINR we go from -5.07 dB to 5.58 dB. Note that the broadcast mode remains an interesting solution even compared to the unicast mode with beamforming which offers an important performance compromise at the cost of a higher antenna complexity.

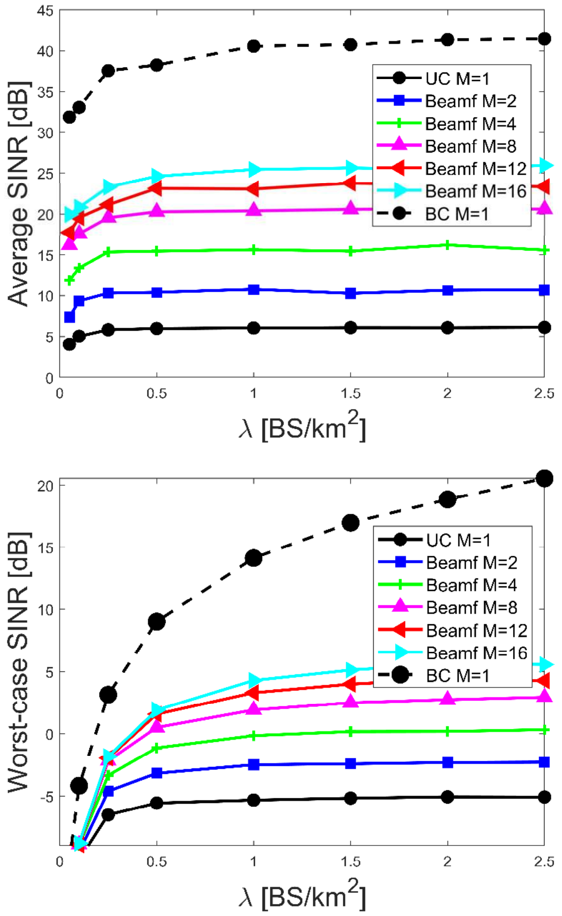

Figure 2. (a) Average SINR and (b) worst-case SINR in unicast (with and without beamforming) and broadcast modes, as a function of λ, for P_{tx} = 0.5W.

5. Conclusion

In this work, an evaluation of the transmission modes of the physical layer of mobile networks has been performed, from the point of view of the distributed base stations following PPP, taking into account the inter-cell interference. We evaluated the performance of unicast (with and without beamforming) and broadcast (using the SFN technique) transmission modes in terms of CDF of SINR, average SINR of the system, and worst case SINR.

These results show that broadcast transmission always outperforms unicast transmission even with beamforming, and this is true regardless of the density of BSs.

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References

[1] L. Liu, Y. Zhou, et al., "Tractable coverage analysis for hexagonal macrocell-based heterogeneous UDNs with adaptive interference-aware CoMP," *IEEE Transactions on Wireless Communications*, 2018, vol. 18, no 1, p. 503-517.

[2] R. Nasri, & A. Jaziri, "Analytical tractability of hexagonal network model with random user location," *IEEE Transactions on Wireless Communications*, 2016, vol. 15, no 5, p. 3768-3780.

[3] A. Shokair, M. Crussiere, et al., "On the coexistence of broadcast and unicast networks for the transmission of video services using stochastic geometry," *IEEE Transactions on Broadcasting*, 2018, vol. 64. no 1 p. 1.

[4] N. El Heni, et X. Lagrange, "Multicast vs multiple unicast scheduling in high-speed cellular networks," *In: VTC Spring 2008-IEEE Vehicular Technology Conference*. IEEE, 2008. p. 2456-2460.

[5] S. Y. Baek, Y. J. Hong, & D. K. Sung, "Adaptive transmission scheme for mixed multicast and unicast traffic in cellular systems," *IEEE Transactions on Vehicular Technology*, 2008, vol. 58, no 6, p. 2899-2908.

[6] P. A. Fam, S. Paquelet, et al., "Analytical derivation and optimization of a hybrid unicast-broadcast network for linear services," *IEEE Transactions on Broadcasting*, 2016, vol. 62, no 4, p. 890-902.

[7] 3GPP. Evolved Universal Terrestrial Radio Access (E-UTRA); *Radio Frequency (RF) system scenarios*. TR 36.942. Version 15.0.0. June 2018.

[8] H. S. Dhillon, & J. G. Andrews, (2013), "Downlink rate distribution in heterogeneous cellular networks under generalized cell selection," *IEEE Wireless Communications Letters*, 2013, vol. 3, no 1, p. 42-45.

[9] F. Baccelli, & B. Blaszczyszyn, "Stochastic geometry and wireless networks: Volume i theory," *Now Publishers Inc*, 2009, vol. 1.

[10] J. Vargas, C. Thienot, et al., "Broadcast-Multicast Single Frequency Network versus Unicast in Cellular Systems," In: 2020 *16th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (50308). IEEE, 2020. p. 1-6.