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Optimizing 5G Performance in Security Threat Situations: A Question of Coverage and Modeling

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Abstract

This article analyzes the means of ensuring reliable and efficient transmission in high-density 5G networks with base stations (BS) in case of crisis or danger. We present a promising approach based on intercellular cooperation through the Multicast Broadcast-Single Frequency Network (MB-SFN) technique. The performance of this approach is compared to that of traditional unicast transmission, with a particular emphasis on evaluating user coverage and finding an optimal trade-off between coverage and key system parameters. This study takes into account that BS are distributed randomly according to a Poisson Point Process (PPP) law to obtain a comparison closer to reality. This uncommon analysis in current literature determines the best strategy to improve 5G coverage in an environment of civil and military security threats.

1 Introduction

In recent years, mobile networks have experienced rapid technological growth with an exponential increase in the number of users and data consumption [1-2]. To meet the expectations of users, mobile network technologies must be constantly improved to reduce latency, speed up transmission speed, and increase capacity. 5G mobile communications represent a major advancement in this trend, bringing significant improvements in terms of data rate and latency. However, it is essential to manage these improvements while considering environmental constraints, spectrum limitations, necessary investments, and energy consumption to ensure a sustainable and effective deployment [1-5].

Techniques such as base station (BS) densification [2-3], massive antennas [4] [6] device-to-device (D2D) communications [1], distributed antenna systems (DAS) [7], beamforming [4] [6], and user equipment scheduling [8] have been widely used to optimize 5G performance. However, user coverage remains a major challenge in fully enjoying the benefits of 5G. Rural areas and massive machine-type communications (mMTC) are particularly difficult to cover. Cell edges also pose problems of uneven coverage and inter-cell interference. It is therefore important to carefully manage coverage planning to avoid gaps [3] [6-8].

Cellular network modeling plays a key role in understanding their limitations and planning their coverage to avoid poorly covered areas. Stochastic geometry is an advanced method that models the positions of network elements (BS and users) using random processes, taking into account their densities [1] [9]. Stochastic geometry uses spatial distributions to simulate real conditions and evaluate important metrics, such as outage probability, energy and spectral efficiency, as well as service quality in terms of signal-to-interference plus noise ratio (SINR). In this study, we consider that BS are randomly distributed (in a square area) according to a Poisson Point Process (PPP) law characterized by the BS density (defined by the number of BS per kilometer square). We address the challenges of coverage and interference management in high-density 5G networks when a security threat situation requires the BS to broadcast an emergency message.

The choice of BS transmission mode is another crucial element in optimizing 5G coverage in case of mass transmissions. Unicast mode is the most frequently used in cellular networks and is considered the standard mode for personal content transmission. This mode allows adjusting the link according to channel conditions to maximize the data rate received by the user. However, when many users request the same service, the data is transmitted several times, which can result in inefficient use of radio resources [4]. It's important to choose the most appropriate transmission mode for each scenario based on factors such as BS density, transmission power, transmission channel effects (including path loss, shadowing, and fading), required signal quality, and available radio resources. To address these challenges, we propose an efficient solution based on the Multicast Broadcast - Single Frequency Network (MB-SFN) intercellular cooperation technique, and we compare its performance to that of classical unicast transmission in various scenarios. We conduct a rigorous analysis to evaluate and predict user coverage in different situations, while finding an optimal trade-off between coverage and key system factors such as BS density and BS transmission power.

2 System model

In this article, we consider high-density BS to be randomly distributed according to a PPP law. We compare the performance of user coverage in both traditional transmission mode (unicast) and cooperative intercellular transmission mode (broadcast via MB-SFN), assuming that all BS with three sectors (each 120° wide) transmit signals in orthogonal frequency division multiplexing in both modes, with the same power, carrier frequency, and bandwidth.

For a user located at a distance $r_{g,i}$ from a given (BS_i), the power of the signal received by the user depends on the path loss exponent α, the fading factor h_i, and the shadowing parameter e^{χ}, as follows:

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

where P_{tx} is the transmission power of the BS, κ is the attenuation coefficient, and α is the path loss exponent, h_i is a randomly distributed exponential variable with a unit rate, χ is a normally distributed random variable with a mean of zero and a variance of σ^2, and $G(\theta)$ is the antenna gain calculated in the direction θ [10].

We model shadowing using a log-normal random variable, noted $y \sim e^{\chi}$, where χ consists of two parts: $\chi = \chi_c + \chi_i$. χ_c takes into account obstacles near the receiver and χ_i takes into account obstacles independent for each BS. Shadowing is defined by its dispersion standard deviation, noted $\sigma = \frac{10}{\sigma_{dB} ln(10)}$, and its total variance can be expressed as $\sigma = \sigma_c^2 + \sigma_i^2$. In the following, we assume that $\sigma_c^2 = \sigma_i^2 = \frac{\sigma^2}{2}$.

Taking into account channel effects, we can express the received signal power from base station BS_i as follows:

$$P_{rx} = P_{tx}\kappa r_{g,i}^{-\alpha} e^{\chi_c} e^{\chi_i} h_i G(\theta) = P_{tx}\kappa r_i^{-\alpha} e^{\chi_c} h_i G(\theta), \tag{2}$$

where r_i is the modified distance between the user and the base station BS_i, which is obtained by taking into account the effect of the obstacle near BS_i (χ_i) on the actual distance between the user and BS_i ($r_{g,i}$). This distance modification $r_i = e^{-\frac{\chi_i}{\alpha}} r_{g,i}$ can be considered as a modification of the original location of the base station BS_i.

3 Performance of conventional and cooperative intercell transmissions

In this section, we compare the performance metrics in terms of SINR and user coverage probability for both unicast and broadcast modes, considering that the BS are randomly distributed according to a PPP and transmit the same content in both modes in the downlink. Maintaining reliable coverage for users is crucial for 5G cellular networks, but can be influenced by several factors such as transmit power, channel effects, carrier frequency, deployment type, and environment. To evaluate coverage quality, the outage probability (p_o) is often used as a performance metric. It measures the probability that a received signal is weaker than a given threshold compared to the interfering signal. Commonly used thresholds for measuring p_o include signal-to-noise ratio (SNR), signal-to-interference ratio (SIR), and signal-to-interference plus noise ratio (SINR). In this study, we calculate the outage probability as the probability that users have a SINR below a pre-defined SINR threshold (S) using the notation $p_o = p\{\gamma < S\}$, which is equivalent to saying that the coverage probability is calculated as follows: $p_c = p\{\gamma \geq S\}$.

In classical transmission mode (unicast), only the serving base station (BS_s) provides a useful signal power ($P_{s,UC}$) while all other BS generate interference. The received signal power $P_{s,UC}$ is therefore calculated based on the serving base station BS_s as: $P_{s,UC} = P_{tx}\kappa r_s^{-\alpha} e^{\chi_c} h_s G(\theta_{s,t})$, where the index s refers to the serving BS and the index t refers to the serving sector of the serving BS. As for the interference power, it is divided into two parts. The first $I_{s,UC}$ is related to the interfering sectors of the serving three sectors BS. The second $I_{i\in\psi/i\neq s,UC}$ is related to the other BS belonging to the study area. The SINR of a user served in unicast mode is therefore expressed as the ratio between the received useful power ($P_{s,UC}$) and the sum of the interference power ($I_r = I_{s,UC} + I_{i\in\psi/i\neq s,UC}$) and the noise power P_N as follows:

$$\gamma_{UC} = \frac{P_{s,UC}}{I_{s,UC} + I_{i\in\psi/i\neq s,UC} + P_N}, \tag{3}$$

with,

$$I_{s,UC} = P_{tx}\kappa r_s^{-\alpha} e^{\chi_c} h_s \sum_{j=1/j\neq t}^{3} G(\theta_{s,j}), \tag{4}$$

$$I_{i\in\psi/i\neq s,UC} = P_{tx}\kappa e^{\chi_c} \sum_{i\in\psi/i\neq s} r_i^{-\alpha} h_i \sum_{j=1}^{3} G(\theta_{i,j}), \tag{5}$$

$$P_N[dBm] = NF + 10log_{10}(KT\omega), \tag{6}$$

where the index j denotes the interfering sectors of the BS and the index i denotes the interfering BS. Note that i belongs to ψ (set of all BS distributed according to PPP), with $i \neq s$. For the noise power P_N, NF is the receiver noise figure, K is the Boltzmann constant, T is the temperature of the receiver system and ω is the bandwidth.

We are now focusing on cooperative intercell transmission (broadcast) using the MB-SFN technique introduced in the 3rd Generation Partnership Project (3GPP) by the LTE Rel-9 standard. This technique involves synchronizing multiple transmitters so they send the same content on the same frequency, thus allowing for a constructive combination of the power received by the receiver. In an MB-SFN area, all BS contribute to the received power (P_{BC}), and also generate interference power (I_{BC}) from delayed signals. For an MB-SFN area composed of a certain number of BS participating in the synchronized transmission (N_{BS}), the SINR in broadcast mode (γ_{BC}) is calculated as follows:

$$\gamma_{BC} = \frac{P_{BC}}{I_{BC}+P_N}, \tag{7}$$

with,

$$P_{BC} = P_{tx} \kappa e^{\chi_c} \sum_{i=1}^{N_{BS}} \delta_i \, r_i^{-\alpha} h_i \sum_{j=1}^{3} G(\theta_{i,j}), \tag{8}$$

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

where δ_i is the weight function of the useful part of a received signal in the MB-SFN area [4].

4 Simulation results and discussion

The considered service area is a square of 400 km sides, where BS are arranged according to a random PPP distribution with a specific density λ. The simulations are based on the parameters of the 3GPP standard [10] using the following values: κ = 0.0295, α = 3.76 and σ_{dB} = 10 dB. Finally, we calculate the noise power P_N with NF = 9 dB, T = 300 K, and ω = 5 MHz.

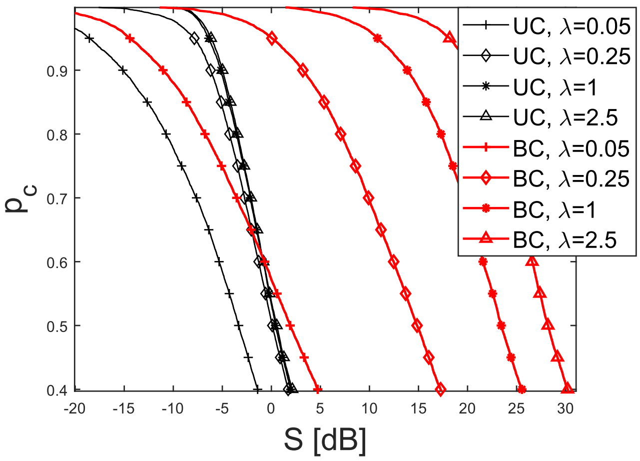

Figure 1. Coverage probability $\boldsymbol{p_c}$ in unicast (UC) and broadcast (BC) modes as a function of target SINR $\boldsymbol{S}$, with transmission power $\boldsymbol{P_{tx}}$ = 0.5 W and different BS density values $\boldsymbol{\lambda}$ (0.05, 0.25, 1, 2.5 BS/Km^2).

In our study, we compare the SINR and coverage probability metrics obtained from 10^4 Monte Carlo simulations. Each simulation represents a different distribution of BS, allowing for a thorough analysis of network performance. We consider that all BS transmit the same content at the same power (P_{tx}), using the same carrier frequency (f_c = 2 GHz) and the same bandwidth (ω = 5 MHz). The results presented in both unicast and broadcast modes (see Figure 1) reveal the crucial influence of BS distribution on the coverage probability (p_c) of users. This is manifested by the variations in p_c with the target SINR S, which varies between -20 dB and 30 dB with a transmission power of 0.5 W and different values of λ. Figure 1 also reveals that p_c decreases with the increase in S, reducing the number of users who can benefit from the service due to degradation of signal quality caused by the interference. This highlights the need to find a balance between performance requirements (target SINR S) and coverage (p_c) to ensure optimal service quality.

In order to evaluate the impact of BS density λ on user coverage with unicast and broadcast transmission modes, we test values ranging from 0.05 to 2.5 BS/Km^2 in Figure 1. The results show that unicast coverage increases to a certain point with increasing λ, then does not significantly progress anymore. This is due to the increase in interference caused by other BS in the study area. On the other hand, broadcast mode shows a continuous increase in coverage even with BS densities λ greater than 0.25 BS/Km^2, which demonstrates the effectiveness of MB-SFN technique in reducing interference and optimizing user coverage in high-density BS environments.

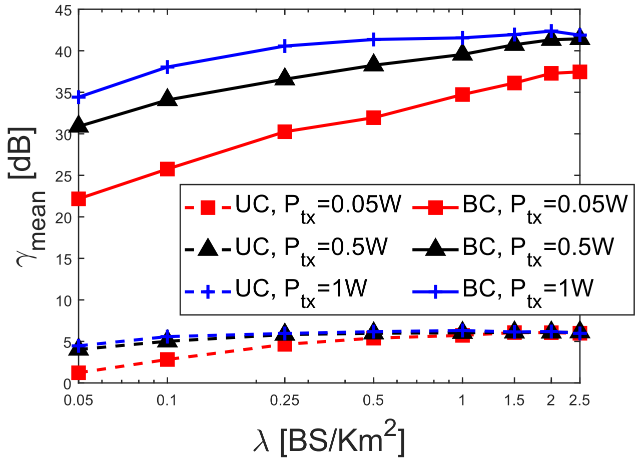

Figure 2. Average SINR γ_{mean} in unicast (UC) and broadcast (BC) modes as a function of BS density λ, for three transmission power values P_{tx} (0.05, 0.5, 1 W).

We now focus on evaluating the performance of the system using the average SINR (γ_{mean}) as a metric. The average SINR is defined as the average value of the SINR obtained from the Monte Carlo simulations. We show in Figure 2 how the average SINR (γ_{mean}) evolves with the BS density by varying λ from 0.05 to 2.5 BS/Km^2 for 3 transmission power levels (P_{tx} = 0.05, 0.5, 1 W). It is clear that as the transmission power P_{tx} increases, the gain in terms of average SINR increases significantly in broadcast mode as opposed to unicast mode where saturation occurs more quickly. For example, comparing γ_{mean} when P_{tx} increases from 0.05 W to 1 W with λ = 0.5 BS/Km^2, γ_{mean} increases from 5.39 dB to 6.17 dB in unicast and from 31.94 dB to 40.57 dB in broadcast. Now, by examining the trade-off between the average SINR and key system factors such as the BS density λ and the transmission power P_{tx}, we find an optimal trade-off for a certain threshold density value. Beyond this value, the SINR does not improve significantly for both modes. We obtain a good trade-off for λ = 0.25 BS/km^2 (unicast mode) and λ = 1 BS/km^2 (broadcast mode).

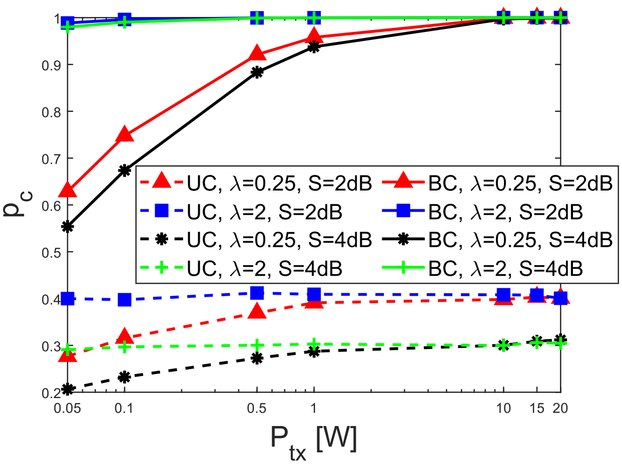

Figure 3. Coverage probability $\boldsymbol{p_c}$ in unicast (UC) and broadcast (BC) modes as a function of transmission power $\boldsymbol{P_{tx}}$, for different combinations of BS density ($\boldsymbol{\lambda}$) and target SINR ($\boldsymbol{S}$).

We remind that the coverage probability results (Figure 1) were obtained with a transmission power (P_{tx}) of 0.5 W. We are now examining the impact of this power on coverage by varying its value from 0.05 W to 20 W (Figure 3) with different combinations of BS density (λ) and target SINR (S). We observe that unicast transmission offers lower coverage than broadcast transmission regardless of the value of P_{tx}. Comparing the coverage gains in unicast and broadcast modes as λ increases from 0.25 BS/Km^2 to 2 BS/Km^2, we see gains of 6.44% (in unicast mode) and 31.67% (in broadcast mode) for S = 4 dB and 8.19% (in unicast mode) and 25.24% (in broadcast mode) for S = 2 dB. The results in Figure 3 also allow us to predict the minimum power required to ensure a certain coverage. For example, to achieve a 90% coverage in broadcast mode with 0.25 BS/Km^2, the minimum required power is 0.4 W (when the target SINR S is set to 2 dB) and 0.6 W (when the target SINR S is set to 4 dB). Examining the trade-off between coverage and transmission power (for both values of λ), we see that a good trade-off is reached for a threshold value of P_{tx} = 0.5 W (in broadcast mode) and P_{tx} = 1 W (in unicast mode).

5 Conclusion

In this paper, we focused on optimizing the performance of 5G networks (in terms of SINR and coverage) in security threat situations. To achieve this goal, we propose broadcast mode transmission with the MB-SFN technique as a reliable solution for transmitting critical information. We show that the MB-SFN broadcast mode is more performant than unicast transmission mode, regardless of the system parameter set. Additionally, we show that, unlike unicast transmission mode, broadcast mode performance is further improved when transmission power or BS density increases. We also pay special attention to optimizing and predicting user coverage in both unicast and broadcast modes, as well as finding the optimal trade-off between coverage and key system parameters. This work can be useful to mobile network operators to plan a mass broadcast of the same emergency message in the event of a security threat in densely populated areas.

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