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Optimizing Energy Efficiency in 5G Small Cell Networks: An Approach Focused on Regulating Power Consumption Related to Transmission and RF Circuits

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Abstract

The deployment of many small cell base stations (BS) is considered as an effective means of improving the performance of next-generation telecommunications networks (5G and 6G) by increasing their coverage, capacity, and data rate. However, this can lead to environmental problems related to high energy consumption. It is crucial to keep on improving the energy efficiency of 5G small cell communications to ensure a good level of service quality while reducing energy costs. This article proposes a solution to this fundamental problem by optimizing the trade-off between energy consumption and spectral efficiency of 5G small cell communication systems, taking into account the energy consumption of the power amplifier and radio frequency (RF) circuits. Furthermore, this article focuses on the evaluation of two classes of RF circuit consumption and how it affects the optimal trade-off between energy consumption and spectral efficiency. We also examine how specific parameters for each class, as well as system parameters, can influence this optimal trade-off. Although our energy consumption model is based on a generic transmitter-receiver structure, it can easily be adapted to analyze other architectures.

1 Introduction

In recent years, the use of small cell base stations (BS) for future generations of telecommunications (5G and 6G) has become increasingly common due to its potential advantages such as improved data rates and increased cellular coverage compared to previous generations, such as 4G [1] [2]. Small cells are small-sized BS that can easily be installed in densely populated areas or in places where it is difficult to build traditional telecommunications infrastructure due to physical or regulatory limitations [3]. However, the need for a large number of small cell BS for 5G communications leads to a high energy cost. Therefore, it is important to find ways to optimize the energy efficiency of these BS to reduce the environmental impacts associated with their use [3-5].

The challenge of balancing between energy consumption and Quality of Service (QoS) has been addressed in many research works [3-4] [6-8]. However, these studies primarily focus on traditional networks where the macro cell transmission distances are relatively large, thus focusing on optimizing energy consumed for transmission. In the case of future small-cell based mobile networks, the BSs are closer to each other and transmission distances are generally shorter. This means that when these small cells are deployed in large numbers, the traffic processed by the baseband units consumes energy that is comparable to or even greater than that of transmission. In this context, this article focuses on optimizing the trade-off between energy consumption and spectral efficiency in 5G/6G small-cell networks, taking into account not only the energy of transmission but also the energy consumed by radio frequency (RF) circuits.

To the best of our knowledge, there seems to be little advanced research on how to optimize the trade-off between energy consumption and spectral efficiency for 5G small cell communications. The theory of trade-off analysis was introduced by Shannon's theorem, but it does not take into account propagation losses, energy consumption of the amplifier, or RF circuit consumption. Our work aims to optimize this trade-off using Shannon's capacity, taking into account the total energy consumption of the system, including the power amplifier and RF circuits. The optimization consists of maximizing the data capacity while minimizing energy consumption, effectively utilizing the frequency band necessary for optimal operation of 5G.

In our study, we evaluate two models for measuring the power consumption of circuits. The first model considers the power of circuits at a constant value, while the second model breaks it down into a constant and an exponentially increasing part, depending on the data rate. Our study also aims to evaluate how factors such as specific parameters of the two models for RF circuit energy consumption (focusing on constant and variable parts) and system parameters (such as the distance between the user and the base station, and the bandwidth) affect the trade-off between energy efficiency and spectral efficiency.

The article is organized as follows: Section 2 describes the energy consumption under QoS constraint and presents the optimization solution for the trade-off between spectral efficiency and energy consumption. Section 3 presents the simulation results of this study. Finally, the conclusions are presented in Section 4.

2 Optimization of the trade-off between energy consumption and spectral efficiency

The channel is modeled with the path loss according to the model proposed by the 3rd Generation Partnership Project (3GPP) [9]. The power received by a user located at a distance $\boldsymbol{d}$ from a BS is expressed by:

$$P_r = P_t \frac{G_t G_r k}{d^\alpha}, \tag{1}$$

where P_t is the transmission power of the BS, k is the attenuation coefficient, α is the path loss exponent, G_t and G_r are the gains of the antennas associated with transmission and reception respectively. The received signal-to-noise ratio (SNR) is defined as the ratio of the received signal power (P_r) to the noise power (P_N) at the receiver. The noise power (P_N) is itself determined based on the Boltzmann constant (K), the temperature of the receiver system (T) and the noise bandwidth (B) as follows: $P_N = KTB$. Thus, the SNR is given by:

$$\text{SNR} = \frac{P_r}{P_N} = P_t \frac{G_t G_r k}{KTBd^\alpha}. \tag{2}$$

Spectral efficiency (θ) measures the efficiency of the use of the frequency band in a communication system. It is calculated by dividing the bit rate (R) by the bandwidth (B) of the communication system, and is expressed in units of bits per second per hertz (bit/s/Hz). On the other hand, energy consumption (E_b) of a communication system is expressed in joules (J) and is calculated by dividing the transmitted signal power (P_t) by the bit rate (R). Thus, the SNR can be expressed using the equations of spectral efficiency $\theta = \frac{R}{B}$ and energy consumption $E_b = \frac{P_t}{R}$, as follows:

$$\text{SNR} = E_b R \frac{G_t G_r k}{KTBd^\alpha} = E_b \theta \frac{G_t G_r k}{KTd^\alpha}. \tag{3}$$

Shannon's theorem is a fundamental law of information that defines the theoretical maximum bit rate that can be achieved through a communication channel for error-free data transmission. According to this theorem, the capacity of a communication channel is determined based on the channel's bandwidth B and the signal-to-noise ratio (SNR) as follows: $C = Blog_2(1 + \text{SNR})$. The capacity C must be chosen to meet the targeted QoS requirements of the service provider as follows:

$$C = Blog_2\left(1 + E_b \theta \frac{G_t G_r k}{KTd^\alpha}\right) \geq R$$

$$\Rightarrow 1 + E_b \theta \frac{G_t G_r k}{KTd^\alpha} \geq 2^\theta. \tag{4}$$

To calculate the energy per bit required to achieve the desired QoS requirements of the end users, we can use Shannon's theorem, which states:

$$E_{b,min} = \frac{KTd^\alpha}{G_t G_r k} \frac{2^\theta - 1}{\theta}. \tag{5}$$

The expression for the minimum energy $E_{b,min}$ (5) is suited for traditional networks where transmission distances are significant and where transmission energy is predominant in the total energy consumption. However, in 5G small cell networks, it is recalled that the transmitters and receivers are close and transmission distances are thus short. Therefore, energy consumed by RF circuits may be greater than or equal to that consumed for transmission. It is therefore important to find an optimal trade-off between spectral efficiency and energy consumption taking into account the characteristics of the system, power amplifier energy consumption and that of RF circuits.

The total consumed power $P_{t,tot}$ is generally defined as the sum of the power used by the power amplifier (P_{pa}) and the power used by the RF circuits (P_{cir}):

$$P_{t,tot} = P_{pa} + P_{cir}. \tag{6}$$

The power P_{pa} is typically estimated based on the amplifier efficiency η_{PA} as follows:

$$P_{pa} = \frac{1}{\eta_{PA}} P_t. \tag{7}$$

Consequently, the total consumed energy (E_{btot}) is defined by the sum of the energy consumed by the transmission E_b' and the circuit energy E_{cir}:

$$E_{btot} = \frac{P_{t,tot}}{R} = E_b' + E_{cir}, \tag{8}$$

with:

$$E_b' = \frac{1}{\eta_{PA}} E_{b,min} = \frac{1}{\eta_{PA}} \frac{KTd^\alpha}{G_t G_r k} \frac{2^\theta - 1}{\theta}. \tag{9}$$

In our study, we examine the circuit power P_{cir} according to two categories of RF power consumption models:

- Class 1 - In this class, the circuit power P_{cir} is defined as a static value

$$P_{cir} = P_c. \tag{10}$$

where P_c is a constant value. Thus, the circuit energy E_{cir} in this class is defined by:

$$E_{cir} = \frac{P_{cir}}{\theta B} = \frac{P_c}{\theta B}. \tag{11}$$

- Class 2 - In this class, the power consumed by the circuits (P_{cir}) is divided into two parts: a constant part (P_c) and a part that varies exponentially with the data rate (R) as follows:

$$P_{cir} = P_c + aR^n. \tag{12}$$

where a is related to the processing complexity. This modeling applies to bit processing tasks, such as channel decoding. The circuit energy E_{cir} in this class is defined as follows:

$$E_{cir} = \frac{P_{cir}}{\theta B} = \frac{P_c + a(\theta B)^n}{\theta B} = \frac{P_c}{\theta B} + a(\theta B)^{n-1}. \quad (13)$$

Our study aims to examine how different parameters of each class of RF circuit energy consumption (such as static and dynamic power) and system parameters (such as the distance between the user and the base station, and bandwidth) affect the optimal values of total energy consumption per bit (E_b') and spectral efficiency (θ). To achieve this goal, we optimize the trade-off between E_b' and θ using equation (10) taking into account the expressions of energy consumed by the circuits in class 1 (11) and class 2 (13). A detailed analysis of this subject will be carried out in the next section for a variety of system conditions. This will help to better understand how these results can be used to improve the energy efficiency of 5G small cell communication systems.

3 Simulation results and discussion

In order to comply with 3GPP standards, the channel parameters were taken from [9] and are consistently used in this article. They are defined as $\alpha = 3.76$ and $k = 0.0295$ for a frequency of 2 GHz. Therefore, we consider $G_t = 15$ dBi, $G_r = 0$ dBi and $\eta_{PA} = \frac{1}{3}$.

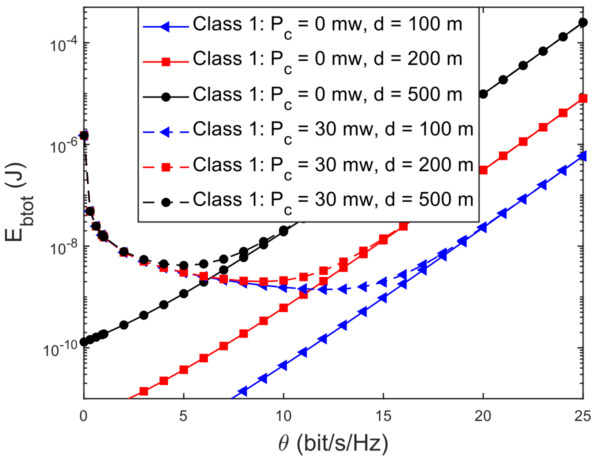

Figure 1. Energy consumed (E_{btot}) as a function of spectral efficiency (θ) for class 1, with B = 2 MHz, P_c = 0 and 30 mW, and different values of d.

The figure 1 shows how the use of static power P_c (class 1) affects energy consumption E_{btot} and spectral efficiency θ by comparing performance at varying transmitter-receiver distances d (100 m, 200 m, 500 m). It is noticed that when P_c is zero, E_{btot} is an increasing function of θ. However, when P_c is equal to 30 mW, it is observed that E_{btot} presents a convex variation with respect to θ, which implies the presence of a global minimum (θ^*, E_{btot}^*). Note that the function $E_{btot} = f(\theta)$ is decreasing when $\theta < \theta^*$ and increasing when $\theta > \theta^*$. This minimum is the optimal point for the trade-off between energy consumption and spectral efficiency. More specifically, the value of θ^* represents the optimal spectral efficiency and the value of E_{btot}^* corresponds to the optimal energy consumption, which translates to the lowest possible energy cost. Let's now examine how distance d affects the optimal trade-off using figure 1. In the case where P_c is zero, it is noticed that when d increases, the total energy consumed (E_{btot}) also increases; this is due to the increase in energy consumed by transmission E_b' (9) which is proportional to the square of the distance. In the case where P_c is non-zero, when d increases, we observe a decrease of optimal spectral efficiency θ^* and an increase of total energy consumed E_{btot}^*. This is due to the increase in energy consumed for transmission E_b' (9) relative to that consumed for the circuits E_{cir} (11), which results in a decrease in spectral efficiency θ (due to the reduction of the total energy consumed E_{btot} which becomes close to E_b').

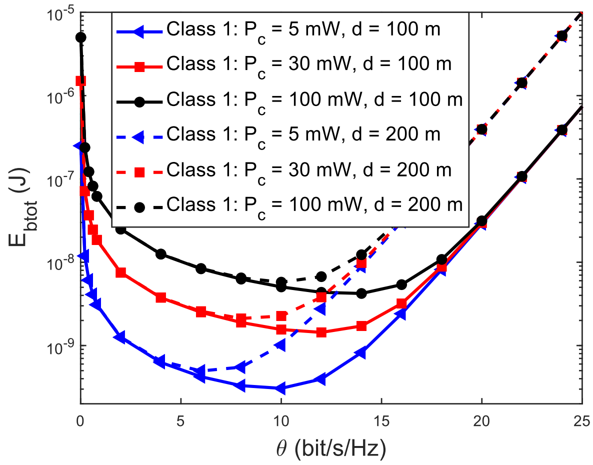

Figure 2. Energy consumed (E_{btot}) as a function of spectral efficiency (θ) for class 1, with B = 2 MHz, and different values of d and P_c.

The figure 2 shows how the variation of P_c (5 mW, 30 mW, 100 mW) affects the optimal trade-off, taking into two distance values d (100 m and 200m). The results of the figure 2 shows that an increase in the static power P_c leads to an increase in the optimal spectral efficiency θ^*. In fact, when P_c increases, the energy consumed by the circuits E_{cir} (11) becomes dominant compared to that consumed for transmission E_b' (9), which leads to an increase in θ due to the reduction of E_{btot} which becomes close to E_{cir}.

After studying the effects of power variations of static circuits P_c and distance d on the optimal trade-offs for class 1, we now wish to evaluate the impact of class 2 specific parameters on the optimal trade-off. Figure 3 shows how variations of parameter a (10^{-11} et 10^{-9}), specific to class 2, affect the optimal trade-off taking into account two values of the bandwidth B (2 MHz and 20 MHz). It is observed that as a increases, the optimal spectral efficiency θ^* increases. This is due to the fact that as a increases, E_{cir} (13) becomes predominant over E'_b (9), leading to an increase in θ due to the reduction of E_{btot} which becomes close to E_{cir}. It can also be seen that as B increases, the optimal spectral efficiency θ^* decreases, as well as the total energy consumed E_{btot}^{*}. This is due to the effect of reducing circuit energy E_{cir} (13) when B increases, which reduces the total energy consumed E_{btot}. Thus, with the increase of B, the energy consumed by the transmission E_b' (9) becomes dominant over the circuit energy E_{cir} (13). Therefore, there is a reduction of θ induced by the reduction of E_{btot} which becomes close to E_b'.

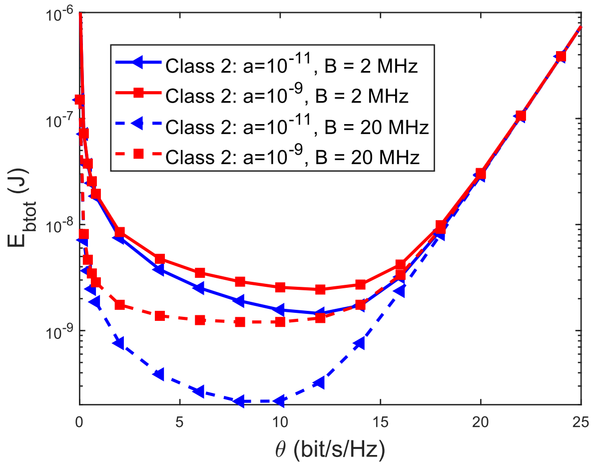

Figure 3. Energy consumed (E_{btot}) as a function of spectral efficiency (θ) for class 2, with d = 100 m, P_c = 30 mW, B = 2 MHz and 20 MHz, n = 1, and $a = 10^{-9}$ and 10^{-11}.

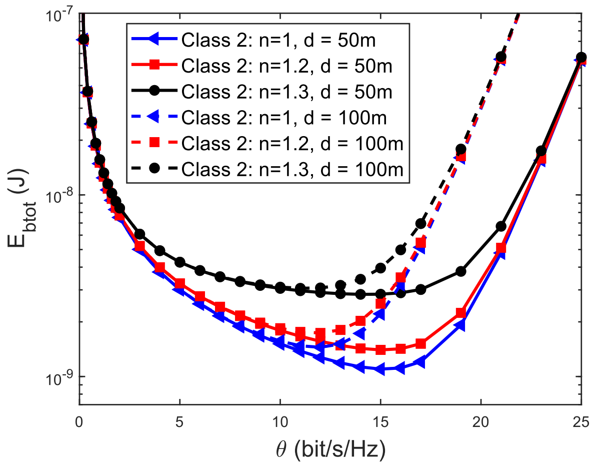

Figure 4. Energy consumed (E_{btot}) as a function of spectral efficiency (θ) for class 2, for $a = 10^{-11}$, P_c = 30 mW, B = 2 MHz, and different values of n and d.

Figure 4 shows how the increase of n, a parameter of the dynamic part of the RF circuit power, affects the optimal spectral efficiency (θ^*) for distances of 50 m and 100 m. It is observed that the increase of n allows to increase the optimal spectral efficiency θ^* and therefore has the same effect as increasing a and P_c.

4 Conclusion

This article examined the trade-off between spectral efficiency and energy consumption in short-range 5G small cell communications using an energy consumption model that included the power amplifier and RF circuits. It was shown that there is an optimal trade-off that can meet QoS requirements while minimizing energy consumption. The impact of two classes of RF circuit consumption on this optimal trade-off was also analyzed. It was shown how specific parameters of each class as well as system parameters affect the optimal trade-off. In summary, the results show that as the transmission distance or bandwidth increases, the optimal spectral efficiency decreases, while as specific parameters of each class of RF circuit consumption increases, spectral efficiency increases.

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