3^{rd} URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Joint optimization of energy consumption and spectral efficiency for 5G/6G point-to-point networks

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Abstract

In this paper, we address the issue of optimizing energy consumption for 5G - and upcoming 6G - small cell networks, while addressing throughput and bandwidth issues. We show that a joint optimization of energy consumption and spectral efficiency is possible in the case of a point-to-point transmission, taking into account the power consumed by the transmission and the baseband units. The impact of the variation of some system parameters on the energy consumption and spectral efficiency is thus evaluated. Particular attention is paid to the search for the optimum energy consumption and spectral efficiency for a variety of system conditions.

1. Introduction

Recent studies already indicate that the number of connected devices is expected to grow exponentially to 100 billion in the next ten years [1]. A traffic forecast indicates that 5G networks could support up to 1,000 times more data than 4G networks in 2018 [1]. To achieve these goals, it is important to reduce their energy consumption, up to 40% by 2030 [1], in order to make their operations profitable. Various approaches are thus considered as inevitable solutions to optimize the energy and spectral efficiencies of 5G/6G networks, such as broadcast transmission, lean carrier design, sleep mode, machine learning, massive MIMO (Multiple Input Multiple Output) and deployment of a large number of small cells [1-3]. This paper is based on the latter approach to provide an optimization solution for 5G/6G point-to-point networks.

Let us note that compared to macro cells (constituting the base of the current networks), small cells (which will be the base of the next generations networks) can be micro cells, pico cells or femto cells, and they are considered as particularly adapted to 5G/6G networks because of the low transmission powers and the short transmission distances (between 10 and 300 m).

Thus, it is expected that the ultra-dense deployment of small-cell base stations (BSs) in 5G/6G networks will provide higher throughput, which improves the system performance [2] [3]. In this context, the huge traffic needs to be handled in the baseband units of small cell BSs, and there are scenarios in which the computational power will become higher than the transmission power (despite lower transmission power requirements for small cell BSs) [2]. It is important to note that the computational power is generally defined by the power consumed by the baseband units, which include the digital processing functions [2] [4-7]. On the other hand, the power consumed in transmission is defined by the power consumed by the RF power amplifier [2] [4-7]. Under these conditions, this paper focuses on the optimization of the energy consumption - spectral efficiency trade-off of small cell networks, taking into account not only the power consumed in transmission but also the computing power.

The study of the energy consumption - spectral efficiency trade-off has been implicitly introduced by Shannon’s theorem [8]. However, Shannon’s theorem considers the AWGN (Additive White Gaussian Noise) channel without considering the path loss, nor the power consumed by the RF power amplifier, nor the computational power, and therefore is not sufficient to determine the optimal operating point of the system. Our work then focused on the optimization of the energy consumption - spectral efficiency trade-off based on Shannon’s capacity [8], but this time considering that the total power consumed by the system takes into account the RF power amplifier and the baseband units. This work also addresses the issue of evaluating the effect of some parameters (computational power, BS-user distance, system bandwidth), on the optimal trade-off between energy consumption and spectral efficiency.

The rest of this paper is organized as follows. Section 2 briefly describes the channel model. Section 3 discusses the optimization of the of the energy consumption - spectral efficiency tradeoff. Section 4 illustrates the simulation results of this study. Finally, conclusions are drawn in Section 5.

2. Channel model

We model the channel with path loss, by referring to the model proposed by the 3GPP (3rd Generation Partnership Project) [9]. The received power by a user located at a distance d from a certain BS can be expressed as:

$$P_r = P_t G_{BS} \frac{k}{d^{\alpha}} \quad (1).$$

where P_t is the transmission power of the BS, G_{BS} is the gain of the BS in the user's direction, k is the path loss factor and α is the path loss exponent.

Posing the path loss in the linear form $L = \frac{d^{\alpha}}{k}$, we can thus write L in dB as $L_{dB} = \alpha 10 log_{10}(d) - 10 log_{10}(k)$. The parameters α and k can be determined based on the 3GPP model for a carrier frequency between 1400 MHz and 2600 MHz [9]:

$$L_{dB} = 128.1 + 37.6 log_{10}(D) + 21 log_{10}(\frac{f_c}{2}) \quad (2).$$

where D is the BS-user distance expressed in km, f_c is the carrier frequency expressed in GHz. In the remainder of the article, we fix f_c to 2 GHz. We obtain $\alpha = 3.76$ and $k = 0.0295$.

3. Optimization of trade-off energy consumption - spectral efficiency

We recall that C. Shannon showed that there is a fundamental tradeoff between energy efficiency and spectral efficiency for reliable communications, but this does not take into account the path loss, nor the power consumed by the RF power amplifier, nor the computational power [8]. In this section, we describe in detail the optimization of the energy consumption-spectral efficiency tradeoff for point-to-point cellular networks, taking these factors into account.

The received SNR by a user can be expressed as $\gamma = \frac{P_r}{P_N}$, where P_r is the received signal power expressed in (1) and P_N is the noise power at the receiver. The power P_N is the thermal noise spectral density for the occupied bandwidth B, expressed as $P_N = KTB$ where K is the Boltzmann constant, T is the temperature of the receiving system.

Now integrating P_r (1) into the expression for the SNR (γ), we thus obtain:

$$\gamma = \frac{P_t}{P_N} G_{BS} \frac{k}{d^{\alpha}}. \quad (3).$$

The spectral efficiency, and the energy consumed (in terms of energy per bit), can be expressed respectively by:

$$\theta = \frac{R}{B} \text{ (bit/s/Hz)} \qquad E_b = \frac{P_t}{R} \text{ (J)} \quad (4).$$

where R is the data rate, P_t is the transmitted power and B is the bandwidth.

Based on (3) and (4), we can express the SNR (γ) as a function of the spectral efficiency as follows:

$$\gamma = \frac{RE_b}{KTB} G_{BS} \frac{k}{d^{\alpha}} = \frac{E_b}{KT} G_{BS} \frac{k}{d^{\alpha}} \theta \quad (5).$$

According to Shannon's theorem, the channel's capacity of a transmission can be computed as $C = Blog_2(1+\gamma)$. With regards to the quality of service (QoS) targeted by the service provider, the channel's capacity of a system must satisfy the following condition:

$$Blog_2(1+\gamma) \geq R. \quad (6).$$

Substituting (5) into (6), we obtain:

$$Blog_2\left(1 + \frac{E_b}{KT} G_{BS} \frac{k}{d^{\alpha}} \theta\right) \geq R \quad (7).$$

Therefore, we can express the energy consumption - spectral efficiency trade-off by:

$$1 + \frac{E_b}{KT} G_{BS} \frac{k}{d^{\alpha}} \theta \geq 2^{\theta} \quad (8).$$

Replacing the inequality with an equality, we obtain the minimum energy per bit E_b as a function of the spectral efficiency θ:

$$E_b = \frac{KTd^{\alpha}}{G_{BS}k} \frac{2^{\theta} - 1}{\theta}. \quad (9).$$

The total power consumed ($P_{t,tot}$) is generally divided into two parts:

$$P_{t,tot} = P_{pa} + P_c \quad (10).$$

where P_{pa} is the power consumed by the power amplifier and P_c is the power consumed by the baseband units. P_{pa} is usually approximated by $P_{pa} = (1+\upsilon)P_t$ where $\upsilon = \frac{F}{\eta_{PA}} - 1$, with η_{PA} is the efficiency of the amplifier and F is the peak factor PAPR (Peak-to-Average Power Ratio) which depends on the modulation used. Therefore, the total energy consumed (E_{btot}) is the sum of the energy E'_b (which is transmission related) and the computational energy E_c (independent of the transmitted energy), as follows:

$$E_{btot} = \frac{P_{t,tot}}{R} = E'_b + E_c \quad (11).$$

where

$$E'_b = (1+\upsilon) \frac{KTd^{\alpha}}{G_{BS}k} \frac{2^{\theta} - 1}{\theta} \quad (12).$$

$$E_c = \frac{P_c}{R} = \frac{P_c}{\theta B}. \quad (13).$$

It can be clearly observed that the result (11) illustrates a nonlinear relationship that couples the total energy consumed per bit E_{btot} with the spectral efficiency θ. The key to the joint optimization of EE and ES relies mainly on this relationship. In this context, an extensive study is carried out in the following section.

4. Simulation Results

In this section, numerical evaluations of the power consumption - spectral efficiency trade-off are performed for a variety of system conditions. Recall that the channel parameters, $\alpha = 3.76$ and $k = 0.0295$ have been calculated (for f_c = 2 GHz) based on the 3GPP model [9]; we also consider a BS gain $G_{BS} = 15\ dBi$ [9], $T = 300K$, $\upsilon = 2$. Regarding the energy consumption, we evaluated it as the total energy consumed per bit (denoted by E_{btot} in the rest of the paper).

We begin our study by evaluating the impact of computational power P_c on the energy consumption – spectral efficiency trade-off. To do so, we sweep its value from 0 W to 1W; its impact is presented in Figure 1 which shows E_{btot} as a function of spectral efficiency (denoted by θ in the simulation). Note that when $P_c = 0$, E_{btot} is an increasing function as a function of θ. On the other hand, when $P_c \neq 0$, we can clearly observe that E_{btot} exhibits a convex variation with respect to θ, which implies the presence of a global minimum. This minimum is the optimal point of the energy consumption – spectral efficiency trade-off. The abscissa value of this point represents the optimal spectral efficiency; the ordinate value corresponds to the optimal energy consumption that results in the lowest possible energy cost. Note that in the rest of the paper, we express the optimal spectral efficiency as θ^* and optimal E_{btot} as $E_{btot}{}^*$.

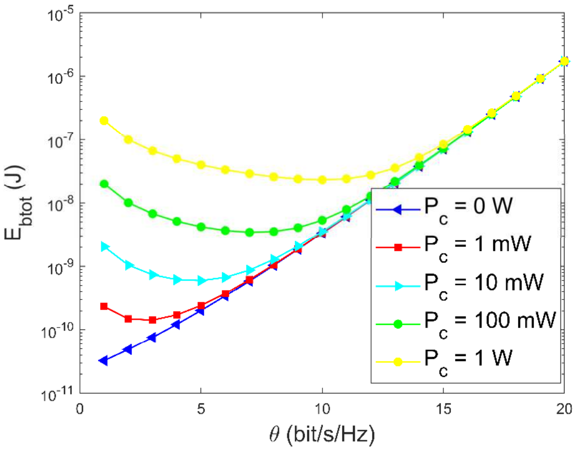

Figure 1. Impact of $\boldsymbol{P_c}$ on the *energy consumption – spectral efficiency* trade-off, for $\boldsymbol{d = 50\,m}$ and $\boldsymbol{B}$ = **5 MHz**.

It can be clearly observed in Figure 1 that E_{btot} is a decreasing function vs. θ when from $\theta < \theta^*$, while E_{btot} is an increasing function vs. θ when $\theta > \theta^*$. This same figure shows that increasing P_c increases the optimal spectral efficiency θ^*. Indeed, when we increase P_c, E_c (13) becomes predominant compared to E'_b (12), and consequently the reduction of the total energy consumed E_{btot} (which becomes close to E_c) imposes an increase of θ.

Now let us analyze the effect of the BS-user distance. Its value has been varied from 10 m to 100 m in figure 2. We notice that it also affects the energy consumption - spectral efficiency trade-off (with P_c = 10 mW and B = 5 MHz). We also notice that when increasing d, the optimal spectral efficiency θ^* decreases. Indeed, when we increase d, E'_b (12) becomes predominant with respect to E_c (13), and consequently the reduction of E_{btot} (which becomes close to E'_b) imposes a reduction of θ.

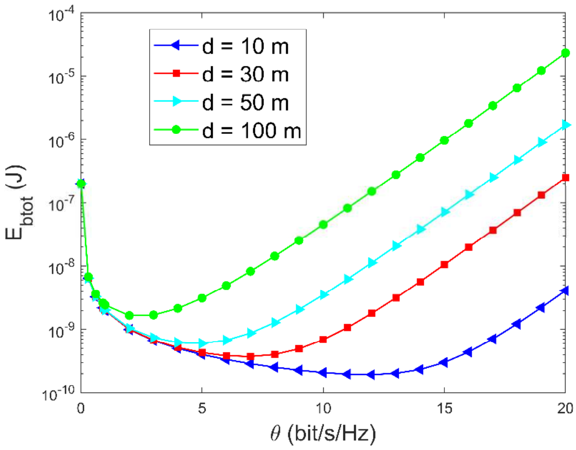

Figure 2. Impact of $\boldsymbol{d}$ on the *energy consumption – spectral efficiency* trade-off, for $\boldsymbol{P_c}$ = 10 mW and $\boldsymbol{B}$ = **5 MHz**.

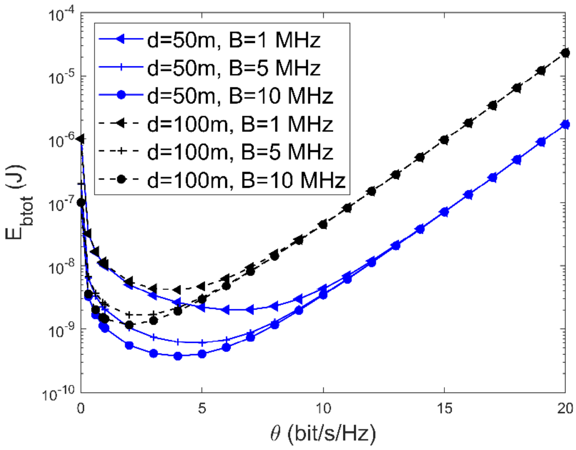

Figure 3. Impact of $\boldsymbol{B}$ on the *energy consumption – spectral efficiency* trade-off, for $\boldsymbol{P_c}$ = 10 mW and for two values of $\boldsymbol{d}$, 50 m and 100 m.

Note that the previous simulations are relative to a bandwidth B = 5 MHz. We now study the effect of using a lower bandwidth (B = 1 MHz) and a higher bandwidth (B = 10 MHz). We observe that increasing the bandwidth from 1 MHz to 10 MHz, decreases the overall energy consumed, but also decreases the optimal spectral efficiency θ^* (whether at d = 50 m or 100 m).

After studying E_{btot} as a function of θ by varying several system parameters, we are now interested in evaluating the optimal metrics θ^* (see Figure 4) and ${E_{btot}}^*$ (see Figure 5) as a function of system parameters. Figures 4 and 5 show these optimal metrics as a function of the BS-user distance, for different values of P_c. In summary, the different results showed that increasing d or B, implies that the optimal spectral efficiency θ^* tends to smaller values; while increasing P_c, implies that θ^* tends to larger values (regardless of the distance d).

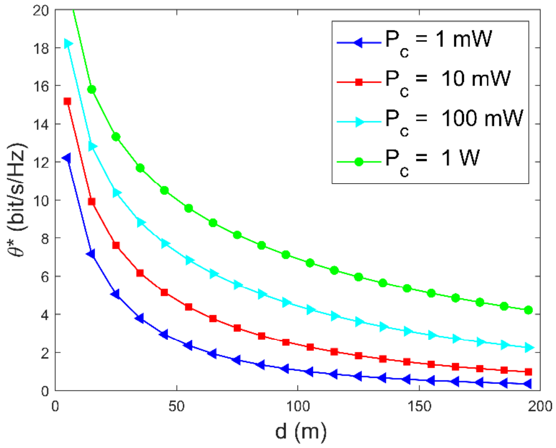

Figure 4. Optimal $\boldsymbol{\theta^*}$ as a function of distance, for $\boldsymbol{B} =$ **5 MHz** and different values of $\boldsymbol{P_c}$.

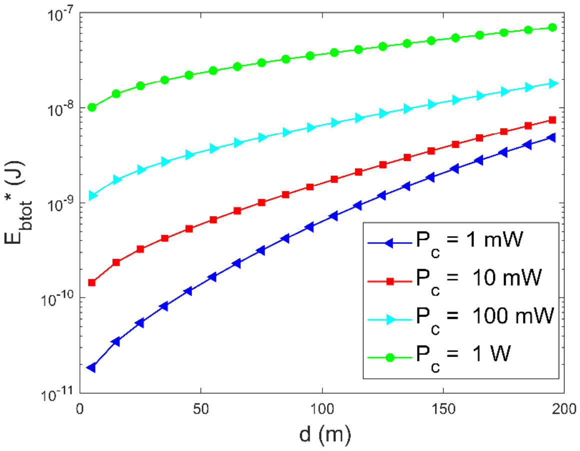

Figure 5. Optimal $\boldsymbol{{E_{btot}}^*}$ as a function of distance, for $\boldsymbol{B} =$ **5 MHz** and different values of $\boldsymbol{P_c}$.

5. Conclusion

Many techniques appear today as promising for minimizing energy consumption and maximizing throughput in 5G (and 6G to come) networks, such as broadcast transmission, lean carrier design, sleep mode, machine learning, massive MIMO (Multiple Input Multiple Output) and deployment of a large number of small cells. In this paper, we are interested in the latter approach to provide a solution for optimizing the energy consumption - spectral efficiency trade-off in the context of 5G (and upcoming 6G) point-to-point networks. Shannon's theorem is the classical concept for studying the energy consumption-spectral efficiency tradeoff, but it does not take into account the path loss, nor the power consumed by the power amplifier and the baseband units, and thus it is not sufficient to determine the optimal operating point of the system. We have optimized the energy consumption - spectral efficiency trade-off with a method that has the advantage of being very simple to implement. The impact of different parameters on the energy consumption-spectral efficiency trade-off has been evaluated (BS-user distance, bandwidth, computing power). We ended our study by analyzing the impact of the parameters on the optimal energy consumption-spectral efficiency trade-off.

6. Acknowledgements

This work was carried out within the framework of the French collaborative project "Covera5Ge" supported DGA and whose partners are CentraleSupélec ENENSYS Technologies and Siradel.

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