Energy and Cost Analysis of Cellular Networks under Co-channel Interference

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***Abstract*—In this paper we carry out an energy efficiency and economic cost analysis of different cellular network designs. Our system model considers the co-channel interference, different amounts of available bandwidths and also the reuse of frequencies. The energy efficiency analysis employs a realistic power consumption model, while the economic analysis focus on infrastructure, spectrum licenses, and energy costs. Our results show that from an economic point of view the bandwidth cost and the number of employed base stations can be the most relevant factors to be balanced, while from an energy efficiency analysis it is more interesting to employ larger bandwidths and to balance the reuse of frequencies and the number of base stations. Moreover, although the system design under these two different points of view can be rather different, we also look into scenarios when the most energy efficient system design may also lead to the best economic option.**

I. Introduction

The main objectives of the first mobile networks were to maximize the coverage area and optimize the system capacity. However, in modern wireless systems, the energy efficiency has become one of the main targets for optimization. This tendency can be justified by the increasing energy costs combined to the growing energy consumption of the information and technology sector (that represents at least 10% of the global energy consumption [1], [2]). Moreover, the demand for data traffic in cellular networks has grown significantly, with forecasts ranging from a hundredfold to a thousandfold increase before 2020 [3]. Thus, the mobile network operators are challenged to meet the growing demands of the users while minimizing costs and consumption.

The energy efficiency of large wireless communication systems has been investigated by many authors, as for instance [4]–[7]. An energy efficiency evaluation framework that includes sophisticated power models for different base station types is proposed in [4]. The authors also consider temporal variations and the spatial distribution of traffic demands over large regions. Later, in [5], we employed the power consumption models of [4] to investigate the energy efficiency of wireless scenarios with multiple antennas at the base station and a single antenna at the mobile station.

The energy efficiency of traditional macro cell deployment scenarios are compared to heterogeneous networks composed of macro and micro base stations in [6]. Results show that the use of micro cells can shift the optimum inter site distance to larger values. Heterogeneous network scenarios are also considered in [7], where a new power consumption model is proposed, which includes the backhaul power in scenarios that can be composed of WLAN access points, macro, micro and pico base stations. The results indicate that in heterogeneous scenarios the relative effect of backhaul power consumption can not be neglected, but this impact is much less significant when larger cells are deployed.

Moreover, at the point of view of the mobile operators the design of a network derogatorily requires an economic analysis. An example is given in [3], including infrastructure, energy and spectrum license costs. It is shown that for a given coverage area, it is more economically interesting to design a dense network with a larger number of base stations, than having a smaller number of base stations where each station covers larger areas. However, factors as the co-channel interference and frequency reuse are not included in the analysis of [3], which can modify the conclusions.

In this paper we perform both economic and energy efficiency analyses for a number of cellular network designs. Similar to [3], we focus on the infrastructure, energy and spectrum costs. However, we extend the analysis as to consider frequency reuse and the impact of the co-channel interference. By comparing economic and energy efficiency designs of a cellular network, we intend to answer *'how much does it cost to make a cellular network greener'*, and *'how much energy is saved when the price of a greener network can be afforded'*. Results show that the conclusions from a total cost analysis and from an energy consumption analysis can differ substantially. While from an economic viewpoint the base station and bandwidth costs are the factors to be balanced, from an energy efficiency perspective it is better to employ a larger bandwidth and balance the frequency reuse and the number of deployed base stations.

The rest of this paper is as follows. The system model, energy and cost analyses are in Section II. Numerical results are given in Section III, and Section IV concludes the paper.

II. System Model

We consider in this analysis the required transmit power from a base station (BS) to a user at the cell edge, given the requirement of a minimum achievable data rate $\mathcal{R}$. The signal-to-noise ratio (SNR) for a user at the cell edge is

$$\rho = \frac{\kappa \cdot P_{tx}}{N}, \tag{1}$$

where κ represents the path loss, P_{tx} is the transmit power per cell, and $N = N_0 \cdot B$ represents the noise power (N_0 is the power spectral density of white Gaussian noise and B is the system bandwidth). The path loss is given by

$$\kappa = \frac{\lambda^2}{(4\pi)^2 \cdot L \cdot M_{\text{cell}}^{\alpha}}, \tag{2}$$

where λ is the wavelength, L is the link margin, α is the path loss exponent, and $M_{\text{cell}} = \sqrt{\frac{2A}{3\sqrt{3}N_{\text{BS}}}}$ is the radius of the cell with hexagonal geometry, with N_{BS} being the total number of BSs employed to cover the serviced area A.

Considering that frequency reuse is employed, we can define the reuse ratio as

$$\mu = \frac{1}{\omega}, \tag{3}$$

where ω is the number of cells within a cluster and that equally share the bandwidth B. For example, Figure 1 illustrates the case of $\omega = 3$, where each cluster is composed of three BSs, identified as **A**, **B**, and **C**. Each BS in the cluster is allocated with a fraction $\mu = \frac{1}{3}$ of the bandwidth in this case. Moreover, it is worth noting that Figure 1 depicts four identical clusters that are co-channel interferers, once the BSs identified by the same letter reuse the same set of frequencies. The larger the cluster size for the same cell radius, the smaller the co-channel interference. However, the larger the cluster size, the smaller the bandwidth allocated to each cell.

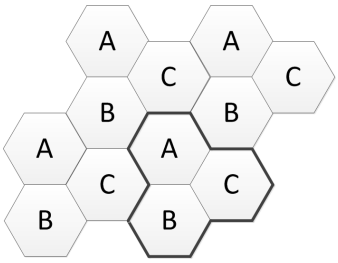

Figure 1. Cellular system employing reuse of frequencies.

In addition, let us remark that, although the co-channel interference is reduced by the frequency reuse technique, it is not fully eliminated, and we can express the signal-to-interference power ratio (SIR) by [8]

$$\text{SIR} = \frac{\kappa \cdot P_{tx}}{P_I} = \frac{1}{6}\left(\frac{3}{\mu}\right)^{\frac{\alpha}{2}}, \tag{4}$$

where P_I is the interference power. Then, the received signal-to-interference plus noise ratio (SINR) for a user at the cell edge is [8]

$$\gamma = \frac{\kappa \cdot P_{tx}}{N_0 \frac{B}{\omega} + P_I} = \frac{\rho}{\mu + f_\mu \rho}, \tag{5}$$

where, to simplify the notation, we introduced the parameter

$$f_\mu = \frac{1}{\text{SIR}} = 6\left(\frac{3}{\mu}\right)^{-\frac{\alpha}{2}}. \tag{6}$$

By considering the SINR into the Shannon's capacity formula, it is possible to obtain the minimum achievable target transmission rate $\mathcal{R}$ per BS, at the cell edge, as

$$\mathcal{R} = \mu B \log_2(1+\gamma) = \mu B \log_2\left(1 + \frac{\rho}{\mu + f_\mu \rho}\right), \tag{7}$$

which can be translated into a required SNR

$$\rho = \frac{\mu\left(2^{\frac{\mathcal{R}}{\mu B}} - 1\right)}{\left(1 - 2^{\frac{\mathcal{R}}{\mu B}} f_\mu + f_\mu\right)}. \tag{8}$$

It is important to remark that ρ is always greater than zero. Moreover, since $2^{\frac{\mathcal{R}}{\mu B}} > 1$, we can observe that the numerator of (8) is always greater than zero, *i.e.*, $\mu\left(2^{\frac{\mathcal{R}}{\mu B}} - 1\right) > 0$. Thus, the denominator of (8) must also respect the same condition:

$$\left(1 - 2^{\frac{\mathcal{R}}{\mu W}} f_\mu + f_\mu\right) > 0, \tag{9}$$

which yields

$$\frac{\mathcal{R}}{B} < \mu \log_2\left(\frac{1+f_\mu}{f_\mu}\right). \tag{10}$$

Then, the inequality in (10) defines the relation between the target transmission rate per BS and the system bandwidth that must be fulfilled to obtain a valid network design.

A. Energy Efficiency

In terms of energy efficiency, we consider the power model in [4], where the total energy consumption of the BS is represented as a linear function composed of the sum of non-load dependent and load dependent terms, as follows

$$\mathcal{E}_{\text{BS}} = P_0 + \Delta_p \cdot P_{tx}, \tag{11}$$

where P_0 represents the non-load dependent power consumption at the minimum non-zero output, and Δ_p is the slope of the load dependent power consumption.

The minimum transmit power per cell, required to achieve the data rate $\mathcal{R}$ for a user at the cell edge, can be found by replacing (8) in (1), so that

$$P_{tx}^{\star} = \frac{\mu\left(2^{\frac{\mathcal{R}}{\mu B}} - 1\right)}{\left(1 - 2^{\frac{\mathcal{R}}{\mu B}} f_\mu + f_\mu\right)} \cdot \frac{(4\pi)^2 N_0 B L M_{\text{cell}}^{\alpha}}{\lambda^2}. \tag{12}$$

Moreover, in practice the BS is limited to use a maximum transmit power $P_{tx}^{\max}$, and the transmit power per cell can be written as $P_{tx} = \min\{P_{tx}^{\star}, P_{tx}^{\max}\}$.

B. Economic Cost

In order to analyze the economic cost of the network, we consider the cost model in [3], where the total cost is dominated by the cost of the spectrum licenses, energy and infrastructure. Thus, the total cost of the network can be written as

$$\begin{aligned} C_{\text{total}} &= C_{\text{infrastructure}} + C_{\text{energy}} + C_{\text{spectrum}} \\ &= C_0 \cdot N_{\text{BS}} + C_1 \cdot (N_{\text{BS}} \cdot \mathcal{E}_{\text{BS}}) + C_2 \cdot B, \end{aligned} \tag{13}$$

where C_0 is the annual cost of each BS, C_1 is the annual cost of energy, and C_2 is the annualized spectrum cost.

III. Numerical Results

In this section, we numerically investigate the energy efficiency and the economic cost for a number of system designs. We consider a target transmission rate per unit area of $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2 and a serviced area of $A = 15$ km^2, unless stated otherwise. Moreover, the carrier frequency is assumed to be $f_c = 2.5$ GHz, corresponding to a wavelength of $\lambda = 120$ mm, the link margin is $L = 10$ dB, the path loss exponent is $\alpha = 3.5$, and $N_0 = -174$ dBm/Hz. For the energy consumption analysis, we only consider the employment of efficient macro BSs with remote radio heads in the system design, whose power model parameters follow [4], and are listed in Table I. In addition, the cost model parameters are based on [3] and are listed in Table II.

Table I
Power model parameters

Maximum transmit power	$P_{tx}^{\max} = 20$ W
Non-load dependent consumption	$P_0 = 84$ W
Slope of the load dependent consumption	$\Delta_p = 2.8$

Table II
Cost model parameters

Annual cost of each BS	$C_0 = 0.02 \cdot 10^6$ \$/BS
Annual cost of energy	$C_1 = 0.876$ \$/Wh
Annual cost of spectrum	$C_2 = 0.0737$ \$/Hz

Figure 2 shows the total network cost as a function of the number of BSs. We consider bandwidth $B \in \{10, 20\}$ MHz, and cluster sizes $\omega \in \{1, 3, 4\}$. Let us remark that the minimum number of BSs for each system design (with different ω and B) is directly related to the condition defined in (10), which associates the target transmission rate and the available bandwidth per BS. From the figure, we can notice that the most cost-efficient solution is the one that employs the lowest bandwidth ($B = 10$ MHz), with $\omega = 3$ cells in a cluster and with the minimum number of BSs, $N_{\text{BS}} = 27$ in this particular example.

It is worth noting that, in this solution, $\omega = 3$ reduces the co-channel interference and, as a consequence, the minimum number of BSs for $B = 10$ MHz is obtained. When $\omega = 4$ is employed, the minimum number of BSs increases since the bandwidth available for each BS decreases. Finally, if frequency reuse is not employed ($\omega = 1$), the available bandwidth per BS increases, however, the co-channel interference (related to f_μ) also increases. As a consequence, due to the relation in (10), the minimum number of BSs also increases with respect to the cases when frequency reuse is employed.

Moreover, although the scenario with $B = 20$ MHz allows the use of less BSs, as shown by Figure 2, the total cost considerably increases in this case, indicating that the spectrum cost may dominate over energy and infrastructure costs. The impact of the BS, energy and bandwidth costs on the total network cost is detailed in Figure 3. We only consider in this figure the total costs for the minimum number of BSs (obtained with $\omega = 3$) for $B = 10$ MHz and

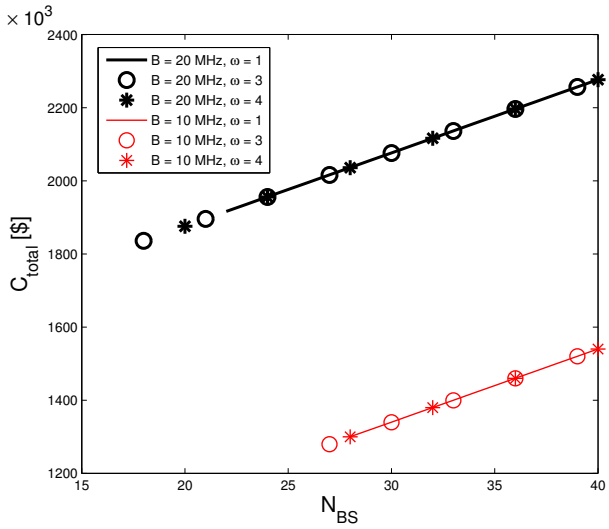

Figure 2. Total network costs for different frequency reuse factors and available bandwidth as function of the number of BSs.

$B = 20$ MHz. In the case of $B = 10$ MHz, the spectrum is responsible for 57.58% of the total cost, fraction that increases to 80.28% when $B = 20$ MHz is employed, which explains why the total network cost with $B = 20$ MHz is much higher than that with $B = 10$ MHz. Moreover, it is also interesting to notice that the energy cost has a very small impact on the total cost, and it is barely visible in the figure (notice that in the figure the energy cost is located between the infrastructure and spectrum costs).

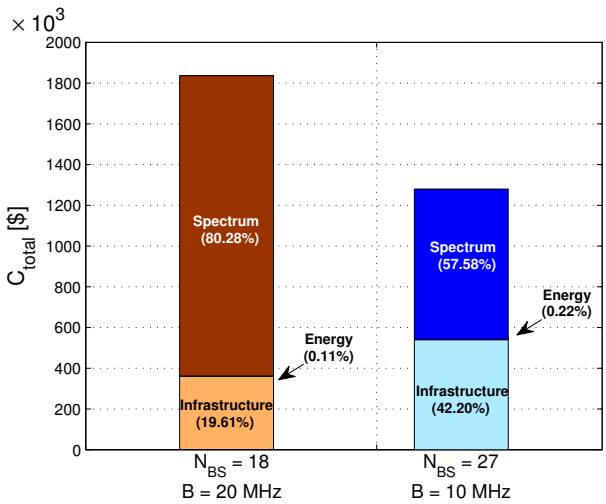

Figure 3. Detailed network costs for the minimum number of BSs for $B = 10$ MHz and $B = 20$ MHz.

The significance of the spectrum cost can also be observed even if we consider a prospective scenario, where the BS cost tends to decrease and the energy cost tends to increase in the near future. For example, if we suppose that the BS cost will drop ten times, while the energy cost will increase ten times in the next years ($C_0' = C_0/10$ and $C_1' = 10C_1$),

for the same coverage area $A = 15$ km^2 and the same transmission rate per unit area $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2, the same conclusions from Figure 2 are obtained, showing that it is more cost-efficient to employ a lower bandwidth and to minimize the number of BSs.

However, it should be emphasized that the results of Figures 2 and 3 consider that the auctioned spectrum is intended to provide coverage for a single area A. Nevertheless, the most usual case is when the provider has multiple coverage areas, so that the total spectrum cost is shared among the multiple coverage areas. As an example, Figure 4 computes the total network cost when the provider has multiple coverage areas of $A = 15$ km^2, each of them with a required transmission rate per unit area $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2. The curves consider that the minimum number of BSs is used and that $B = 10$ MHz or $B = 20$ MHz.

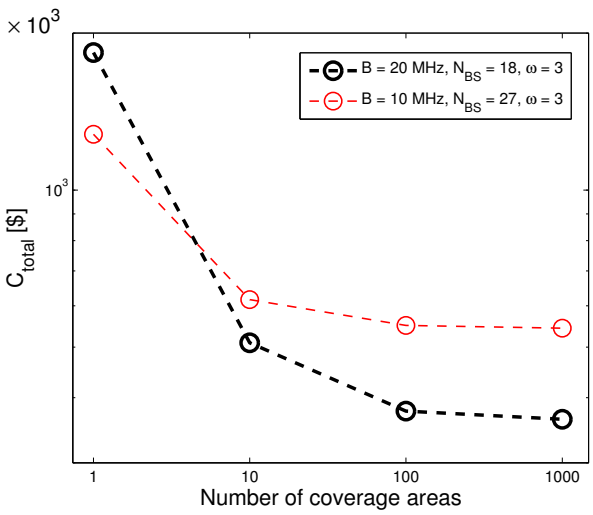

Figure 4. Total network costs as function of the number of coverage areas.

When only one coverage area is considered, the results of Figure 4 are the same as in Figure 2. The spectrum cost of $C_2 = 0.0737$ \$/Hz dominates in the total network cost, and the use of a narrower bandwidth is more cost-efficient. However, when the number of coverage areas increases, which decreases the spectrum cost per area, we can observe that the system design that employs a wider bandwidth (and consequently a smaller number of minimum BSs) becomes the most cost-efficient solution. For instance, in the case of having 10 coverage areas of $A = 15$ km^2, the spectrum cost per area is of 0.00737 \$/Hz, which contributes with a smaller fraction in the total cost, such that the reduction of the number of BSs is the most relevant factor to the economic optimization of the network.

The detailed cost of the BSs, energy and bandwidth is shown in Figure 5 for the scenario with 10 coverage areas[1] of $A = 15$ km^2. The spectrum is now responsible for 11.95% of the total cost in the case of $B = 10$ MHz, and of 28.93% when $B = 20$ MHz is employed. The most relevant factor in this case becomes the infrastructure cost, responsible for 87.60% of the total cost with $B = 10$ MHz, and of 70.67% with $B = 20$ MHz.

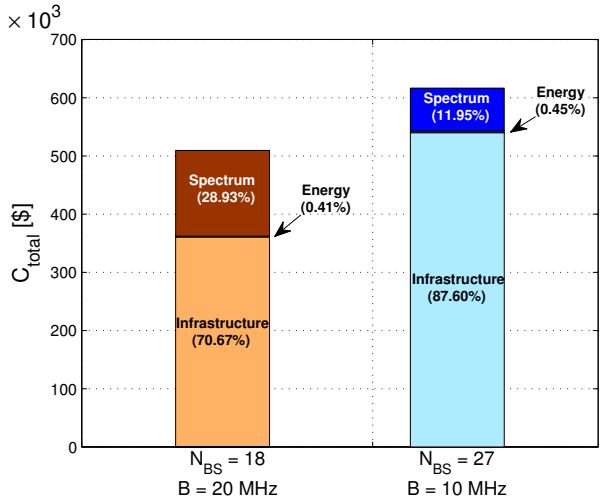

Figure 5. Detailed network costs per coverage area for the minimum number of BSs for $B = 10$ MHz and $B = 20$ MHz considering 10 coverage areas.

An energy efficiency analysis is considered in Figure 6, where we compute the total energy consumption, which we define as $\mathcal{E}_{\text{total}} = N_{\text{BS}} \cdot \mathcal{E}_{\text{BS}}$, to provide a minimum transmission rate of $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2 for a single serviced area of $A = 15$ km^2 as a function of the number of BSs. From the figure we can notice that, in terms of energy consumption, it is always more interesting to use wider bandwidths, with higher ω. Thus, if we compare Figures 2 and 6, we observe that the optimal solution from the energy efficiency point of view differs from the optimal solution from the economic cost point of view, as it is more energy efficient to employ a larger bandwidth with $\omega = 4$, while it is more economically interesting to employ a smaller bandwidth and $\omega = 3$.

In terms of energy efficiency, the design with a smaller bandwidth $B = 10$ MHz only outperforms the solution with $B = 20$ MHz when the reuse of frequencies is employed in the first and there is no reuse in the latter. As with frequency reuse the co-channel interference is reduced, it is possible to employ a lower transmit power. However, the most energy efficient solution is obtained when an increased available bandwidth is combined with a higher frequency reuse, which minimizes the required transmit power of each BS. This is illustrated in Figure 7, where we can observe that the best solution is obtained with $B = 20$ MHz and $\omega = 4$. It is important to remark that, although the solution with $\omega = 4$ requires more BSs than the design with $\omega = 3$, which implies in a higher non-load dependent energy consumption, the load dependent consumption has great relevancy in the energy consumption analysis, and the

[1]The reduction of the spectrum cost can also be motivated by the future employment of techniques that provide the dynamic allocation of the spectrum, such as cognitive radio techniques.

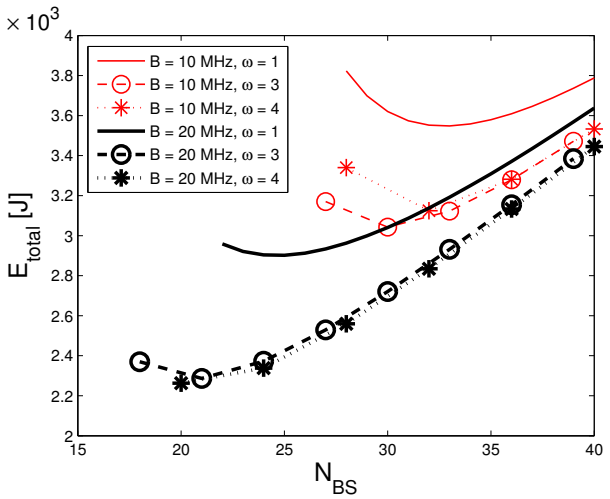

Figure 6. Energy costs for different frequency reuse factors and bandwidth as function of the number of BSs.

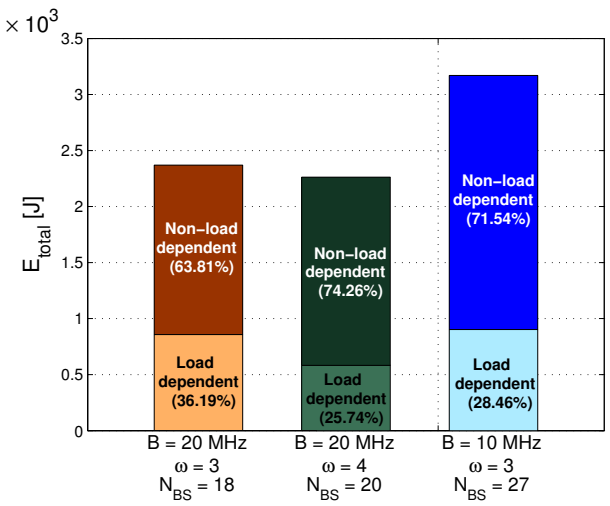

Figure 7. Detailed energy costs per coverage area for the minimum number of BSs for $B = 10$ MHz and $B = 20$ MHz.

solution with a higher frequency reuses gets more energy efficient due to the significant power savings provided by the reduced co-channel interference.

Table III compares the most efficient system designs from the economic and energy efficiency points of view. For instance, the first line of the table shows that the best economic design for a network with a single coverage area costs 1279.6 $ and consumes 3.17 J. On the other hand, the same network with the best energy efficiency design costs 1875.7 $ (46.6% more) and consumes 2.26 J (28.7% less). It is worth noting that the total costs and system designs differ considerably if one coverage area is considered. However, when the number of coverage areas increases, the most economic and the most energy efficiency solutions present closer total cost and energy cost results. This is observed because the infrastructure cost gets more relevant and both

Table III
MOST EFFICIENT SYSTEM DESIGNS FROM THE ECONOMIC AND ENERGY CONSUMPTION POINTS OF VIEW.

Coverage areas		Total cost [$]	Energy cost [J]	ω	N_{BS}	B [MHz]
1	Economic	1279.6	3.17	3	27	10
	Energy	1875.7	2.26	4	20	20
10	Economic	509.44	2.37	3	18	20
	Energy	549.35	2.26	4	20	20
100	Economic	376.81	2.37	3	18	20
	Energy	416.72	2.26	4	20	20
1000	Economic	363.55	2.37	3	18	20
	Energy	403.46	2.26	4	20	20

solutions employ more similar system designs with a wider bandwidth ($B = 20$ MHz) and a reduced number of BSs.

IV. Conclusion

We investigate a cellular network design from two different points of view: energy efficiency and economic cost. We analyze scenarios where the co-channel interference is considered, different bandwidths can be available, and that different frequency reuses can be employed. Our results show that it can be more energy efficient to employ a higher system bandwidth and to minimize the required transmit power of each BS by balancing the number of BSs and the reuse of frequencies. On the other hand, from an economic point of view, different conclusions may be obtained, once the BS and the bandwidth costs are the most relevant factors to be balanced to obtain the most cost-efficient solutions. Moreover, it can be noted that the optimal solutions for both the economic and the energy analysis present closer results when the fraction of the infrastructure cost prevails over the spectrum cost in relation to the total cost.

Acknowledgement

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