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Energy Efficiency vs. Economic Cost of Cellular Networks under Co-channel Interference

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***Abstract*—In this paper we analyze the energy efficiency and the economic cost of cellular network designs, by taking into account the co-channel interference among cells, different amounts of available bandwidths, and frequency reuse. 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 mobile network industry has witnessed an explosive growth. Wireless communications networks have become much more pervasive than what could have been imagined when the cellular concept was first developed in the 1960s and 1970s [1]. The widespread adoption of mobile networks created the demand for improving the system capacity, through the adoption of robust transmission techniques (*e.g.*, error correction techniques, multiple antennas, orthogonal frequency-division multiple access – OFDMA, *etc.*). However, due to the increasing energy costs, combined to the growing energy consumption of the information and technology sector, which is said to represent at least 10% of the global energy consumption [2], [3], modern wireless network designs now face a '*green*' challenge, *i.e.*, to provide technological solutions for the growing data traffic demand, while reducing the overall energy consumption of the network [4].

One way to improve the energy efficiency of mobile networks is by reducing the coverage area of the cells. Users located at the cell-edges are oftenly considered the reference for the network quality, since they typically have the smaller QoS [5]. Then, since the power usually decreases with the logarithm of the distance [1], less power is needed to reach the user at the cell-edge if the cells are smaller. Thus, heterogeneous networks composed by micro, pico, or femto cells are very promising for this context [6], [7].

The energy efficiency of large wireless communication systems has been investigated by many authors, as for instance [8]–[11]. An energy efficiency evaluation framework that includes sophisticated power models for different base station types is proposed in [8]. The authors also consider temporal variations and the spatial distribution of traffic demands over large regions. Later, in [9], we employed the power consumption models of [8] 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 [10]. Results show that the use of micro cells can shift the optimum inter site distance to larger values. Heterogeneous networks scenarios are also considered in [11], where the authors analyze the energy efficiency and propose a new power consumption model that includes the backhaul power in scenarios that can be composed of WLAN access points, and 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. An energy efficiency analysis for heterogeneous scenarios considering the co-channel interference with low, medium and high traffic demands is presented in [7]. It is shown that an increased deployment density can improve the energy efficiency in high traffic demand scenarios.

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 [4], including infrastructure, energy and spectrum license costs. It is shown that for a given coverage area, it is more economically efficient 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 [4], which can modify the conclusions. The work in [12] presents an energy and cost analysis for different homogeneous cellular scenarios with composed of macro and micro cells, including an interference model. The results show the effects of the cell radius variation on the cost and the energy efficiency. However regarding the frequency reuse, it is considered in all results that each cell employs all the available bandwidth, thus the frequency reuse factor is equal to one.

In this paper we perform economic and energy efficiency analyses for a number of cellular network designs. Similar to [4], 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. The main goal of this investigation is to compare the 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 afford*'. Our results show that the conclusions obtained from the total cost analysis and the energy consumption analysis can differ substantially. While from a economic point of view the base station and bandwidth costs are the factors to be balanced, from an energy efficiency perspective it is more efficient 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, economic and energy consumption analyses are presented in Section II. Results focusing on the network total costs and energy efficiency are numerically evaluated for different scenarios in Section III, and Section IV concludes the paper.

II. SYSTEM MODEL

Let us consider the transmission from a base station (BS) to a user at the cell-edge. The network is constrained to deliver to this user a minimal achievable data rate of $\mathcal{R}$. Note that this scenario represents the worst case in terms of QoS for this network. The signal-to-noise ratio (SNR) for this user is

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

where κ represents the path loss, P_{tx} is the transmit power at this cell, $N = N_0 \cdot B$ is the noise power, N_0 is the power spectral density of additive white Gaussian noise, and B is the system bandwidth. The path loss is given by [13]

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

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 that equally share the bandwidth B. For example, Figure 1 illustrates the case of $\omega = 3$, where each cluster is composed by three BSs, identified as **A**, **B**, and **C**. Each BS in the cluster is allocated a fraction $\mu = \frac{1}{3}$ of the bandwidth in this case. Moreover, it is worth noting that Figure 1 depicts four identical clusters and, the BSs identified by the same letter reuse the same set of frequencies, and therefore are co-channel interferers. 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.

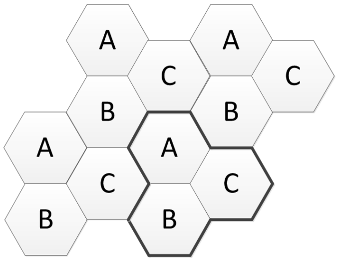

Figure 1. Cellular system employing reuse of frequencies.

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 [13]

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

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 [13]

$$\text{SINR} = \frac{\kappa \cdot P_{tx}}{N_0 \frac{B}{\omega} + P_I} = \frac{\text{SNR}}{\mu + \frac{\text{SNR}}{\text{SIR}}}. \tag{5}$$

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

$$\begin{aligned} \mathcal{R} &= \mu\, B \log_2 (1 + \text{SINR}) \\ &= \mu\, B \log_2 \left(1 + \frac{\text{SNR}}{\mu + \frac{\text{SNR}}{\text{SIR}}}\right), \end{aligned} \tag{6}$$

which can be translated into a required SNR

$$\text{SNR} = \frac{\mu\left(2^{\frac{\mathcal{R}}{\mu B}} - 1\right)}{\left(1 - 2^{\frac{\mathcal{R}}{\mu B}} f_\mu + f_\mu\right)}, \tag{7}$$

where, to simplify the notation, we introduced the parameter

$$f_\mu = \frac{1}{\text{SIR}} = 6\left(\frac{3}{\mu}\right)^{-\frac{\alpha}{2}}. \tag{8}$$

It is important to remark that the SNR is always greater than zero. Moreover, since $2^{\frac{\mathcal{R}}{\mu B}} > 1$, we can observe that the numerator of (7) is always greater than zero, *i.e.*, $\mu\left(2^{\frac{\mathcal{R}}{\mu B}} - 1\right) > 0$. Thus, the denominator of (7) must also respect the same condition, so that

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

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 [8], where the total energy consumption of the BS is represented as a linear function composed by 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 (7) 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 [4], 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 perform an economic cost and energy efficiency analysis for a number of cellular system designs. We consider a carrier frequency of $f_c = 2.5$ GHz (which corresponds to a wavelength of $\lambda = 120$ mm), with the path loss exponent $\alpha = 3.5$, the link margin $L = 10$ dB, and $N_0 = -174$ dBm/Hz. Moreover, we initially consider the serviced area $A = 10$ km^2. Regarding the economic analysis, the cost model parameters are based on [4] and are listed in Table I. For the energy consumption, we consider in our model the use of efficient macro BSs with remote radio heads, whose power model parameters follow [8], and are listed in Table II.

Table I
COST MODEL PARAMETERS

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

Figure 2 illustrates the total network cost as a function of the number of BSs. We consider a target transmission rate per unit area of $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, bandwidth $B \in \{10, 20, 40\}$ MHz, and cluster sizes $\omega \in \{1, 3, 4, 7\}$.

Table II
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	$\Delta_p = 2.8$

It should be emphasized 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 narrowest bandwidth ($B = 10$ MHz), with $\omega = 1$ (no frequency reuse is employed in a cluster) and with the minimum number of BSs, $N_{\text{BS}} = 23$ in this particular example.

Note that for $B = 10$ MHz, as ω increases, the minimum number of BSs also increases, as the available bandwidth for each BS decreases. In this example, at least 23 BSs are needed for $\omega = 1$, 24 for $\omega = 3$ and $\omega = 4$, while 35 BSs are needed for $\omega = 7$. Although in the solution with $\omega = 1$ the co-channel interference (related to f_μ) increases, the available bandwidth per BS increases (each cell is allowed to employ all the available bandwidth), and as a consequence, the minimum number of BSs for this particular case with $B = 10$ MHz is obtained.

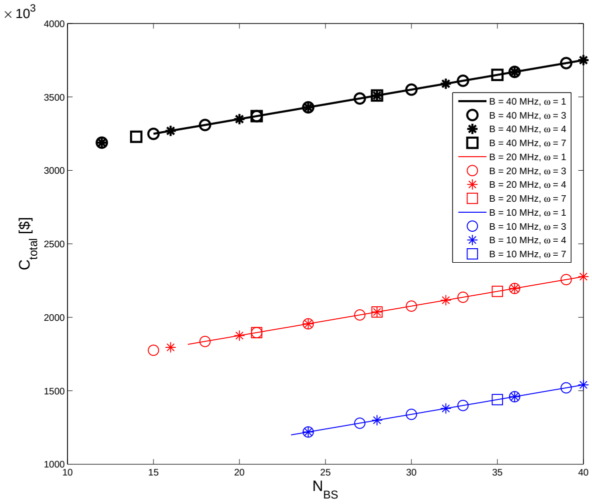

Figure 2. Total network costs for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, and different frequency reuse factors and available bandwidth as function of the number of BSs.

Moreover, although the scenarios with $B = 20$ MHz and $B = 40$ MHz allow the use of less BSs, 15 BSs for $B = 20$ MHz and 12 BSs for $B = 40$ MHz 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. As illustrated in Figure 3, for a higher target transmission rate per unit area of $\mathcal{R}_{\text{area}} = 40$ Mbps/km^2, the minimum number of BSs for the scenarios with $B = 10$ MHz, $B = 20$ MHz and $B = 40$ MHz increases to 40, 24 and 18 BSs, respectively. Moreover, let us also remark that this result is directly related to the condition defined in (10).

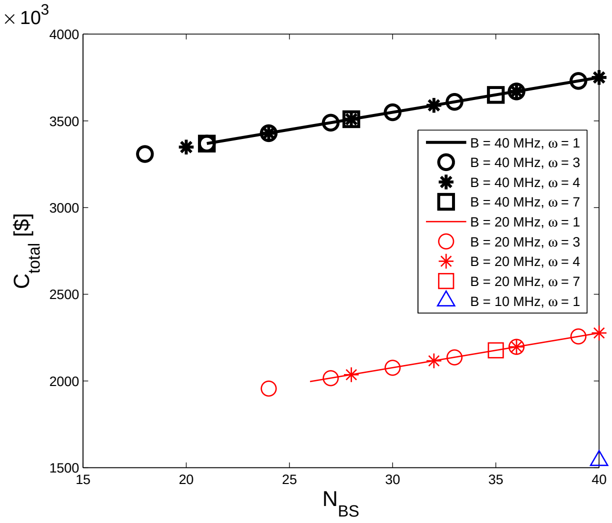

Figure 3. Total network costs for $\mathcal{R}_{\text{area}} = 40$ Mbps/km^2, and different frequency reuse factors and available bandwidth as function of the number of BSs.

The impact of the BS, energy and bandwidth costs on the total network cost is detailed in Figure 4. We only consider in this figure the total costs for the minimum number of BSs (obtained with $\omega = 1$ for $B = 10$ MHz, and $\omega = 3$ for $B =$ 20 MHz and $B = 40$ MHz) for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2. It can be observed that for the scenario with $B = 10$ MHz, the spectrum represents 61.43% of the total cost. If the available bandwidth increases, it can be noticed that the spectrum has a significant increase in the total network costs, as for $B =$ 20 MHz the bandwidth is responsible for 83.01% of the total cost, and for $B = 40$ MHz this fraction increases 92.43%. Although the solution that employs the narrowest bandwidth requires more infrastructure (*i.e.*, higher number of BSs) if compared to the scenarios with $B = 20$ MHz and $B =$ 40 MHz, the spectrum cost prevails in the total network cost analysis. As a consequence, the most cost efficient solution in this case if the one that employs the narrowest bandwidth 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). Similar results are obtained for $\mathcal{R}_{\text{area}} = 40$ Mbps/km^2, with the spectrum cost representing 47.80% of the total cost for $B = 10$ MHz, 75.33% considering $B = 20$ MHz, and 89.06% for $B = 40$ 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 $C_1' = 10\,C_1$), for the same coverage area $A = 10$ km^2 and the transmission rate per unit area $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, the same conclusions from Figure 2 are obtained, showing that it is more cost efficient to employ a narrower bandwidth and to minimize the number of BSs.

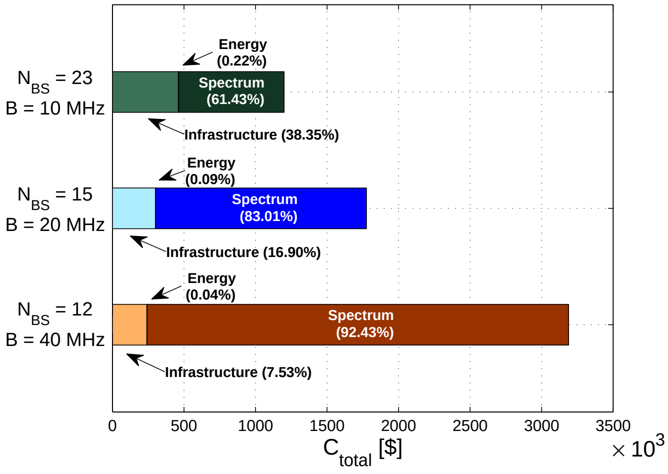

Figure 4. Detailed network costs for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, and the minimum number of BSs for $B = 10$ MHz, $B = 20$ MHz and $B =$ 40 MHz.

However, it should be emphasized that the results from Figures 2, 3, and 4 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 5 computes the total network cost when the provider has multiple coverage areas of $A = 10$ km^2, each of them with a required transmission rate per unit area $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2. The curves consider that the minimum number of BSs is used and that $B = 10$ MHz, $B = 20$ MHz or $B = 40$ MHz.

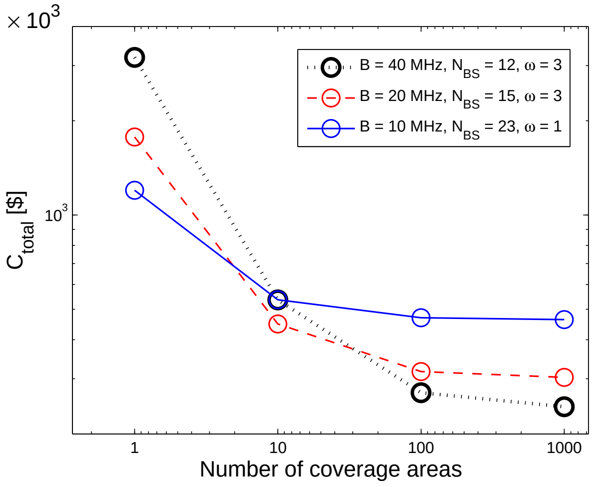

Figure 5. Total network costs as function of the number of coverage areas.

When only one coverage area is considered, the results of Figure 5 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 $A = 10$ 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 6 for the scenario with 100 coverage areas[1] of $A = 10$ km^2. The bandwidth represents 1.57% of the total cost for $B = 10$ MHz, while this fraction increases to 4.66% of the total cost in the case of $B = 20$ MHz, and it is 10.88% when $B = 40$ MHz is employed. The most relevant factor in this case becomes the infrastructure cost, responsible for 97.85% for $B = 10$ MHz, 94.83% of the total cost with $B = 20$ MHz, and of 88.64% with $B = 40$ MHz.

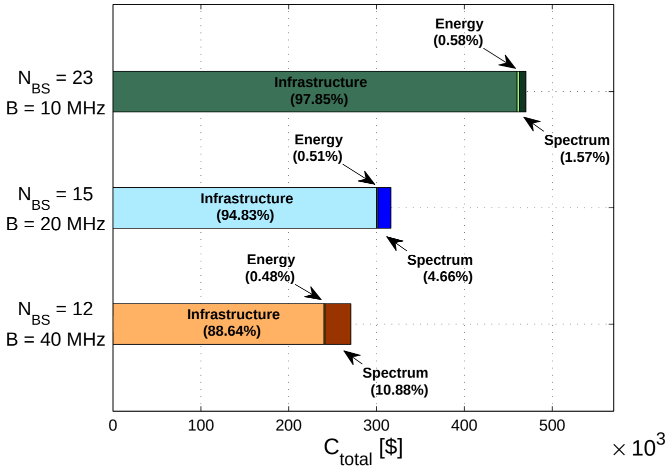

Figure 6. Detailed network costs per coverage area for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, and the minimum number of BSs for $B = 20$ MHz and $B = 40$ MHz considering 100 coverage areas.

An energy efficiency analysis in considered in Figure 7, 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 $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2 for a single serviced area of $A = 10$ 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 the scenario with $\omega = 4$ presenting a slight advantage over $\omega = 7$. Thus, if we compare Figures 2 and 7, 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 wider bandwidth with $\omega = 4$, while it is more economically interesting to employ a narrower bandwidth and $\omega = 3$.

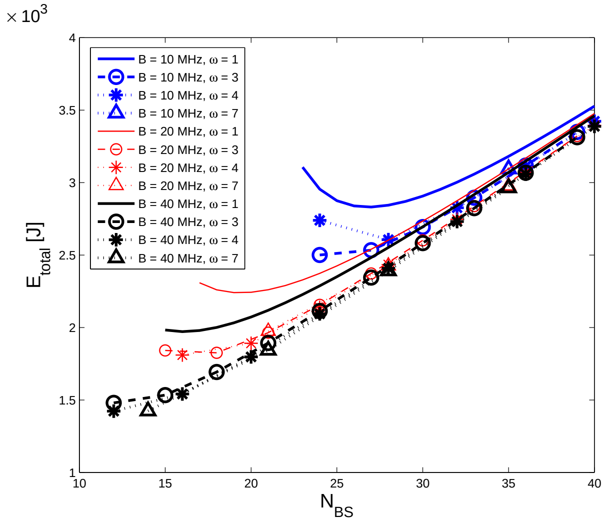

Figure 7. Energy costs for different frequency reuse factors and bandwidth as function of the number of BSs.

In terms of energy efficiency, the design with a narrower bandwidth $B = 10$ MHz only outperforms the solution with $B = 40$ 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 8, where we can observe that the best solution is obtained with $B = 40$ MHz and $\omega = 4$. It is important to note that, although the solutions with $\omega = 4$ and $\omega = 7$ have close performances, the scenario with $\omega = 7$ provides power savings due to the reduced co-channel interference (lower load dependent power consumption), the solution with $\omega = 4$ requires less BSs, implying in a lower non-load dependent energy consumption.

Figure 9 shows the minimum energy consumption in function of the target transmission rate per unit area $\mathcal{R}_{\text{area}}$ for $B = 10$ MHz, $B = 20$ MHz, and $B = 40$ MHz. For example, for $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2, the most energy efficient solution has $B = 40$ MHz, $\omega = 4$, and it requires 12 BSs. Note that in terms of the energy consumption analysis, even for different target transmission rates, it is more efficient to employ wider bandwidths, as a lower transmit power is required.

An economic analysis is showed in Figure 10, which compares the minimum total costs for a number of target transmission rates per unit area $\mathcal{R}_{\text{area}}$ considering 100 cov-

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[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.

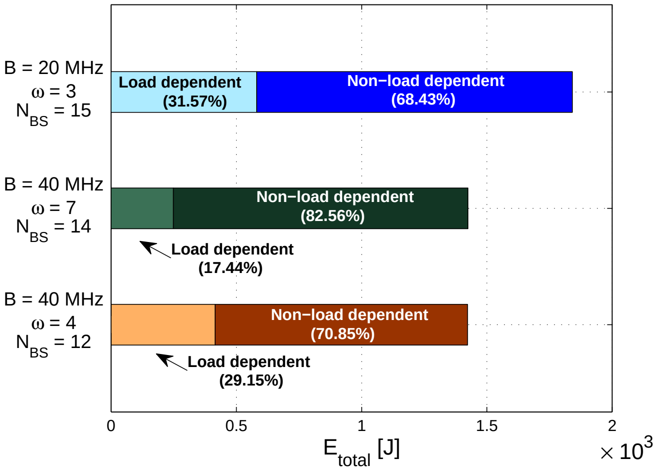

Figure 8. Detailed energy costs per coverage area for the minimum number of BSs for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2, and $B = 20$ MHz and $B = 40$ MHz.

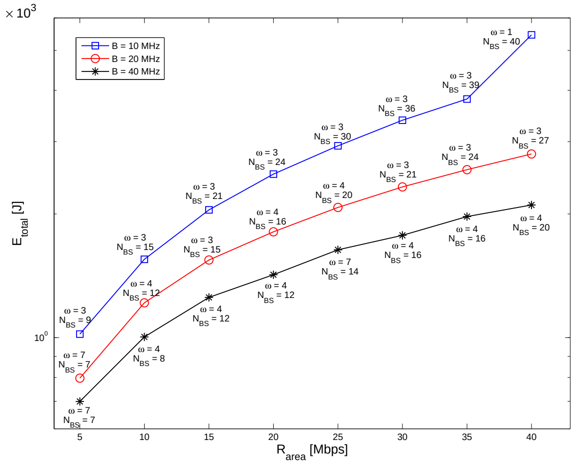

Figure 9. Minimum energy consumption for different transmission rates per unit area $\mathcal{R}_{\text{area}}$.

erage areas. Note that for most of the target transmission rates it is more economical to employ a wider bandwidth. As shown in Figure 5 and detailed in Figure 6, the most relevant factor in the total cost analysis is the infrastructure, and the solution with $B = 40$ MHz requires the minimum number of BSs for any $\mathcal{R}_{\text{area}}$ considered in this analysis. However, it can be observed that for $\mathcal{R}_{\text{area}} = 15$ Mbps/km^2 the scenario with $B = 20$ MHz outperforms the solution that employs $B = 40$ MHz. As both solutions require the same number of BSs with $N_{\text{BS}} = 12$, the lower bandwidth cost for $B = 20$ MHz provides the most efficient solution in terms of the economic analysis.

Table III details the most efficient system designs from the economic and energy efficiency points of view for $\mathcal{R}_{\text{area}} = 20$ Mbps/km^2. For instance, the first line of the table shows that the best economic design for a network with a single coverage area total costs are 1199.6 $\times 10^3$ \$, with energy consumption of 3105.8 J. On the other hand, the same network with the best energy efficiency design costs 3188.6 $\times 10^3$ \$ (165.8% more) and consumes 1422.7 J (54.19% 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, and present the same results for 100 coverage areas. This is observed because the infrastructure cost gets more relevant and both solutions employ more similar system designs with a wider bandwidth ($B = 40$ MHz) and a reduced number of BSs.

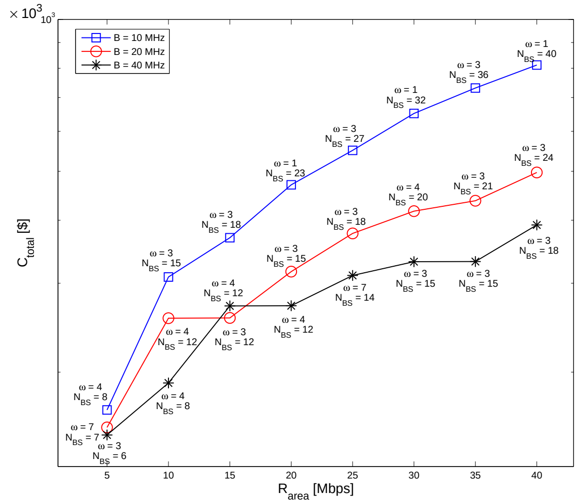

Figure 10. Minimum total costs for 100 coverage areas and different transmission rates per unit area $\mathcal{R}_{\text{area}}$.

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

Coverage areas		Total cost $\times 10^3$[\$]	Energy [J]	ω	N_{BS}	B [MHz]
1	Economic	1199.6	3105.8	1	23	10
	Energy	3188.6	1422.7	4	12	40
10	Economic	448.98	1841.4	3	15	20
	Energy	535.98	1422.7	4	12	40
100	Economic	270.72	1422.7	4	12	40
	Energy	270.72	1422.7	4	12	40

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 also 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.

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