Noname manuscript No.
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On the Importance of Technology for Energy Caps on Cellular Networks

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June 28, 2016 Rev 1208
File: https://thomas.gerad.ca/svn/silvia/publications/Netnomics_2015/Netnomics_2015.tex

Abstract **Keywords** First keyword · Second keyword · More

1 Introduction

According to the NOAA[1] (National Oceanic and Atmospheric Administration), 2014 was measured to be the warmest year globally since the records began in 1880. Solid research work, conducted from different standpoints, suggests that such temperature change is largely caused by human activities, especially the release of carbon dioxide (CO_2) and other greenhouse gases (GHGs) through the burning of fossil fuels, which are abundant and therefore cheap [12]. The whole information and communication technology (ICT) sector has been calculated to represent about 2% of global CO_2 emissions and about 1.5% of global CO_2 equivalent (CO_2e)[2] emissions in 2007 [13]. The well known SMART2020 report predicted that the overall ICT footprint will less than double by 2020 while, according to [6], the footprint of mobile communications alone could almost triple within the same time period. The reason behind the continuous and rapid development of mobile communications is to be found in the fundamental role of connectivity in social and economic relationships. To get a sense of the booming spread of wireless communications, one can think that, 15 years after the first phone call using Global System for Mobile Communications (GSM) occurred in 1991, the number of GSM users was over 2 billion. Today, the total number of mobile subscriptions in the world has reached nearly 7.5 billion, equivalent to 95.5% of the world population.

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[1] NOAA is a federal agency within the United States Department of Commerce focused on the conditions of the oceans and the atmosphere.

[2] CO_2e is used to express the impact of each different greenhouse gas in terms of the amount of CO_2 that would create the same amount of warming.

In recent years, the research world has grown awareness toward the fundamental role of mobile communications in the global warming problem. Examples of exhaustive reviews of green mobile challenges can be found in [14, 7, 5]. One of the topic that received great attention by green mobile networking researchers is the concept of energy-aware management of existing networks. Several network operation techniques have been proposed in literature (see, among others, [4, 10, 11]), all exploiting the typical geographical and temporal variability of mobile traffic. For instance, consider a medium to large city, characterized by one or more business areas as well as by residential zones. In weekdays, during the central hours of the day, most of the subscribers will be at work, thus mostly concentrated in business areas; on the other hand, during nighttime or in the weekends, the traffic will converge on residential areas. Mobile networks are designed to guarantee the agreed quality of service in peak traffic conditions; however, when the traffic is lower, many base stations (BSs) may result unnecessary to the coverage of the area and the service of the active subscribers. To reduce the energy waste, some cells can be put to sleep while the remaining active cells are in charge of the area coverage. If needed, active cells can zoom out, i.e., increase their transmitted power to eliminate possible coverage holes left by sleeping BSs.

While energy-aware management represents a good starting point to reduce mobile networks' carbon footprint, more decisive solutions may be necessary. In our previous work [2, 3] we have introduced the idea of jointly optimizing the network design, based on a trade-off between capital expenses (CapEx) and operational ones (OpEx), and the network operation to follow the traffic variations over time. Therefore, we developed the joint planning and energy management (JPEM) optimization framework. We demonstrated that, during off-peak periods, networks deployed using the joint optimization show an increased capacity of adapting their activation pattern to the traffic variability. The higher the network flexibility, the greater the energy savings that can be obtained in the network operation phase.

In this paper, we take advantage of the flexibility produced by the JPEM modeling approach to investigate the limitations to which a mobile operator would be confronted if asked to reduce its carbon footprint, and therefore, its consumed energy. We conduct the study trying to answer to the following questions:

1. *How can operators meet the energy caps, and how much would it cost?*

We show the measures that network operators can take to comply with the carbon reductions, highlighting the energy savings that can be obtained as well as the costs that are incurred.

2. *What factors have the largest influence on the ability to meet the energy caps?*

Each topology shows a different ability to adapt to the imposed energy reductions. We investigate the elements that are mostly responsible of such variability, we motivate their impact and show its entity on the topology behavior.

Table 1: Transmission and consumption features of each BS configuration.

Configuration	Installation Cost (€)	Transmitted Power (dBm/W)	Consumed Power (dB/W)	Traffic Capacity (Mb/s)	Coverage Distance (m)
$C1$	30000	43 / 19.9	31.3 / 1350	210	1230
$C2$	10000	38 / 6.3	21.6 / 144.6	70	850
$C3$	1000	21 / 0.1	11.7 / 14.7	70	241

3. *How can the authority implement the energy caps fairly for all network topologies?*

Because energy requirements must apply to all the networks deployed in a certain area, they are rather general and do not take into account the differences among the involved networks. Thus, we consider legacy topologies with various characteristics, as well as different condition of technology availability. We compare the obtained results and show why carbon markets are necessary.

The reminder of this paper is structured as follows. ....

2 Preliminary Considerations

This section is devoted to the presentation of the joint planning and energy management (JPEM) framework first proposed in [2]. In this paper, we decided to include the complete formulation to provide the reader with a detailed insight into the trade-off that we want to study. The JPEM framework consists in finding, at the same time, the optimal base station (BS) location and capacity taking into account that such access devices will be able to be managed (on/off operation) during the day following a traffic demand pattern.

2.1 Choice of Base Station Parameters

We consider LTE base stations features displayed in Table 1. Configuration $C1$ constitutes an example of macro BS, while configurations $C2$ and $C3$ are respectively micro and pico BSs. We assumed that a network operator already owns the right to deploy some access station in the available candidate sites, so the "Installation Cost" only reflects the price of the access device itself. Site rentals and labor expenses are not considered in this analysis. "Transmitted Power" refers to the emitted power in peak load conditions, in this paper considered invariable with traffic, while the heading "Consumed Power" represents the mean equipment power consumption (including power amplifier, signal generator, cooling system and microwave link).

Power and capacity values were extracted from [1], while the coverage radius was calculated by using the Cost-231 Hata model for suburban scenarios [8]. Finally, in order to quantify the energy consumption in terms of monetary expenses, we assume the energy cost to be equal to 0.2 Euro per kWh and the network lifetime to be about 14 years.

Table 2: Approximated traffic profile in a typical day for a suburban area.

Index	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
Start	00:00	2:00	4:00	8:00	10:00	13:00	18:00	20:00
End	2:00	4:00	8:00	10:00	13:00	18:00	20:00	24:00
Duration	2 h	2 h	4 h	2 h	3 h	5 h	2 h	4 h
ρ_t	0.8	0.55	0.25	0.45	0.65	0.8	0.9	1

2.2 Traffic Variations

A daily traffic profile has to be considered to account for the variations of the traffic intensity in the service area. The considered profile for a suburban area, based on downlink traffic measurements as in [9], is defined in Table 2, which displays the start and end time of each period, its duration as well as the related fraction of traffic load ρ_t. To realize such traffic distribution, we define a set of *traffic test points* (TPs), representing traffic aggregation centers which are uniformly spread in the area. For every time interval we assign each traffic test point with a random value uniformly selected between 20 and 40 Mb/s, together with a random number in the $[0, 1]$ interval. The first value denotes the amount of traffic provided by a test point to the network only if the second value is less than or equal to ρ_t. Furthermore, we introduce *coverage test points* that do not produce any traffic. They are disposed on a regular grid overlaying the area to ensure the total coverage in the dimensioning phase even in the off-traffic regions.

2.3 The Basic Optimization Model

The idea at the basis of the joint design and operation optimization is simple. Assume that our goal is to obtain the best network topology from an energy management point of view, at the same time keeping the capital costs as low as possible. To ensure an efficient energy management through a cell sleeping mechanism, the deployed topology has to be provided with enough flexibility to follow the traffic variations during the day. Therefore, the JPEM model minimizes a trade-off between capital and operation costs and, at the same time, provides an example of energy-efficient network management.

Parameters	**Description**
I_c	Set of coverage TPs
I_t	Set of traffic TPs
S	Set of CSs to locate BSs
K_j	Set of possible configurations for a BS located in $j \in S$
T	Set of time intervals
δ_t	Duration of time period $t \in T$
p_{it}	Traffic provided by the TP $i \in I_t$ in period $t \in T$
c_{jk}	Capacity of the BS located in $j \in S$ with configuration $k \in K_j$
γ_{jk}	Installation cost for a BS located in $j \in S$ with configuration $k \in K_j$
ϵ_{jk}	Power consumption for a BS located in $j \in S$ with configuration $k \in K_j$
β	Weight parameter used to trade-off the objective function
φ	Cost of the energy consumption over the entire network lifetime ($\varphi = 1$)
a_{ijk}	Binary, equal to 1 if TP $i \in I_c \cup I_t$ is covered by a BS installed in $j \in S$ with configuration $k \in K_j$
Variables	**Description**
z_{jk}	Binary, equal to 1 if a BS is installed in $j \in S$ with configuration $k \in K_j$
y_{jkt}	Binary, equal to 1 if a BS installed in $j \in S$ with configuration $k \in K_j$ is active in period $t \in T$
x_{ijt}	Binary, equal to 1 if TP $i \in I_t$ is assigned to a BS located in $j \in S$ in period $t \in T$

Table 3: JPEM parameters and variables.

Parameters and variables are defined in Table 3. The JPEM optimization model can be described as follows:

$$\min \quad (1-\beta)\sum_{j\in S}\sum_{k\in K_j} z_{jk}\gamma_{jk} + \beta\varphi\sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T}\epsilon_{jk}\delta_t y_{jkt} \tag{1}$$

$$\text{s.t.} \quad \sum_{j\in S}\sum_{k\in K_j} a_{ijk}y_{jkt} \geq 1 \quad \forall i \in I_c \cup I_t, t \in T \tag{2}$$

$$x_{ijt} \leq \sum_{k\in K_j} a_{ijk}y_{jkt} \quad \forall i \in I_t, j \in S, t \in T \tag{3}$$

$$\sum_{j\in S} x_{ijt} = 1 \quad \forall i \in I_t, t \in T \tag{4}$$

$$\sum_{i\in I_t} x_{ijt}p_{it} \leq \sum_{k\in K_j} c_{jk}y_{jkt} \quad \forall j \in S, t \in T \tag{5}$$

$$y_{jkt} \leq z_{jk} \quad \forall j \in S, k \in K_j, t \in T \tag{6}$$

$$\sum_{k\in K_j} z_{jk} \leq 1 \quad \forall j \in S \tag{7}$$

$$z_{jk}, y_{jkt}, x_{ijt} \in \{0,1\} \quad \forall i \in I_t, j \in S, k \in K_j, t \in T \tag{8}$$

The objective function (1) is composed by a CapEx term, which accounts for the installation cost of the chosen devices, and an OpEx term, which considers the energy consumption in the operational setting, summing up the power required by each BS during the time periods in which it is turned on. The weight parameter β is used to tune the trade-off between the two components of the objective function. The first set of *global coverage constraints* (2) provides a

Table 4: Parameters used to generate the test scenarios.

Scenario	Area (km)	CSs	Traffic TPs	Coverage TPs
S_60_30	2×2	60	30	121
S_100_50	3×3	100	50	256
S_120_60	4×4	120	60	441
S_180_80	5×5	180	80	676
S_220_100	4×4	220	100	441
S_250_120	6×6	250	120	961

basic coverage of the service area by guaranteeing that all TPs lay in the coverage radius of at least one switched-on BSs. In addition, *traffic TP coverage constraints* (3) insure that every traffic TP is assigned to an active BS that covers it. *Assignment constraints* (4) impose that every traffic TP is assigned to exactly one BS in each time period. Idle TPs that are not requesting traffic in a certain time interval are as well assigned to a BS, but they do not contribute to fill its capacity. *Capacity constraints* (5) guarantee that each BS has enough capacity to satisfy the assigned traffic in every time period. *Activation constraints* (6) state that an access device can be switched on at any time only if the device is actually installed in that location. Every candidate site (CS) can host at most one type of access station, as specified by *configuration constraints* (7). Finally, *domain constraints* (8) assert that all the three groups of variables are binary.

2.4 Test Scenarios

Using the base station parameters and traffic profile described above, we define six test scenarios reported in Table 4. They are ordered from the smallest to the largest in terms of number of CSs and traffic TPs. The name of each scenario indicates its number of candidate sites and traffic test points in the form of $S\_\#CSs\_\#TPs$. The second entry represents the measure of the side of the square service area, while the second one is the number of candidate sites randomly located in the area and initially available to the operator. Next, the numbers of traffic and coverage test points are reported.

The proposed mathematical model was implemented using AMPL programming language and optimized with CPLEX solver. For each instance, we set the solver to provide solutions after 2 hours 30 minutes of computation, or once an optimality gap of 2% or less was achieved. However, for the largest instances, we were forced to run the instances for several hours to reach optimality gaps lower than 20%. Since the objective of this paper is not to provide precise cost results, but to give an idea of the impact of energy consumption constraints on the operator's expenses, we believe that the high optimality gap of a few instances will not impact the validity of our analysis.

3 Meeting Energy Caps: How and At What Price?

Network operators can meet energy caps in one of two ways: 1) implement energy management on their legacy network or, if this is not enough, 2) add some more base stations. The second measure would provide some flexibility for a better energy management in case the first measure was not suitable. In this section, we try to quantify the costs and potential savings of each option. In order to do this, we need to explain how legacy networks are built in the first place.

3.1 Legacy Network Design

We assume that current networks are designed to minimize total capital expense subject to some coverage constraints with no consideration for energy savings. We also assume that only large base stations of type $C1$ are currently available. This is not unreasonable since small base stations are only starting to be used. Because we don't have realistic costs for leasing a site, we assume that the only cost for installing an access device is the equipment cost itself. We also assume that the technology for energy management is present in the base stations but is not currently used.

Based on these assumptions, we design the legacy networks using the JPEM model with the following modifications.

- Since the network design only accounts for capital expenditures, while operation costs are neglected, parameter β in objective function (1) is set to 0, to obtain:

$$\sum_{j \in S} \sum_{k \in K_j} z_{jk} \gamma_{jk} \tag{9}$$

- Activation variables y_{jkt} are replaced by installation variables z_{jk} in constraints (2), (3) and (5), since no network management mechanism is used.
- For the same reason, activation constraints (6) are eliminated, as well as the time dimension (index t) of the problem.
- In order to ensure network coverage in every traffic condition, only the highest value of traffic produced by each test point during the day is considered in constraints (5): $\hat{p}_i = \max_t p_{it}$.

We define the resulting network CapEx as C_0^c. The operation cost C_0^e of always-on base stations during the whole network lifetime is calculated as:

$$\varphi \sum_{j \in S} \sum_{k \in K_j} \epsilon_{jk} z_{jk} \tag{10}$$

Both C_0^c and C_0^e are considered as reference values for the next calculations.

Table 5: Zero-cost energy reduction: energy savings with cell sleeping in legacy topology.

Scenario	Energy Savings
S_60_30	-34.72%
S_100_50	-40.42%
S_120_60	-31.25%
S_180_80	-9.64%
S_220_100	-41.88%
S_250_120	-26.56%

3.2 Zero-Cost Solution: Legacy Network Operation Management

As we assumed that the pre-installed network devices are provided with the required technology, the easiest solution for the operator facing energy consumption limitations is to enable a management mechanism on its network. The objective is to achieve the maximum power savings allowed by the legacy topology. If the obtained energy reductions are enough to comply with the carbon regulations, then no other action is required and the network operator is able to reach its goal without any extra expenses or topology changes. In order to model the operation of a pre-installed network, the basic framework described in Section 2.3 is modified as follows:

- When managing an existing network, only operation expenditures have to be minimized; thus, parameter β in objective function (1) is set to 1, to obtain:

$$\varphi \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk} \delta_t y_{jkt} \tag{11}$$

  In what follows, we will refer to this new OpEx value as C^e_{sleep}.
- To account for the devices already in place, a new set of binary parameters τ_{jk} is introduced, which are equal to 1 only if a base station is installed in site j with configuration k, 0 otherwise. Since the topology is fixed and no additional device can be installed, parameters τ_{jk} replace variables z_{jk} in constraints (6).
- No additional device can be installed, so constraints (7) are dropped.

For every tested scenarios, Table 5 reports the savings obtained when an energy management mechanism is performed on the initial network. The percentages refer to the OpEx value C^e_0 in always-on network conditions. Depending on the initial configuration, implementing a cell sleeping mechanism on legacy networks may allow discretely high energy savings. Legacy topologies only deploy macro cells, which are positioned in the area so as to be able to serve the maximum amount of traffic provided during the day in every test point location. This design strategy involves an important over-provisioning of the network resources, which proves to be useful during off-peak periods when operation management is performed. So, for instance, we can achieve energy savings of as much as 42% with no extra CapEx for scenario S_220_100, but savings of less than 10% in case of scenario S_180_80. Results between 25% and 40% were obtained for the other four scenarios, measuring an average of about 26% OpEx reduction overall.

The fact that high power savings can potentially be attained with no additional costs represents great news for those operators whose network topology is composed only by older technology, less efficient cells. Such an elevated initial energy consumption could lead us to think that legacy networks would be in disadvantage when trying to comply with some imposed energy caps. Instead, the amount of energy that would go to waste in unmanaged topologies translates in saved energy once an on/off mechanism is implemented.

3.3 Legacy Network Upgrade

If the energy reduction limits imposed to the network operator are not met by adopting an energy-efficient network management, some changes in the network topology may be necessary. With the aim of reducing the carbon emissions, and thus, the energy consumption, more redundancy has to be added to the current topology to increase the network flexibility. This redundancy will be useful to turn off a higher number of base stations during low traffic periods, improving the effectiveness of the cell sleeping mechanism.

In order to maintain the new CapEx expenses as low as possible, the network operator can exploit the set of candidate sites that we assumed it already owns and where no access device is yet installed to deploy supplementary base stations. Additional capital costs and total operation expenses are jointly minimized, while the operation of the access stations (initial and newly deployed) is managed to respect the OpEx limitations. Once again, we modify the JPEM formulation in Section 2.3 to compute the upgraded networks:

- The access devices that are part of the initial topology cannot be removed or changed, but only managed. We define S' as the set of sites j occupied by legacy BSs, and K'_j as the set of the chosen configurations for such access devices. Therefore, variables z_{jk} corresponding to pre-installed base stations are fixed to 1.

$$z_{jk} = 1 \ \ \forall j \in S', k \in K'_j \tag{12}$$

- In objective function (1), the same weight has to be assigned to both additional CapEx and total OpEx terms. To do so, parameter β should be set to 0.5; however, without altering the outcome of the optimization, we removed parameter β from the formulation, which is equivalent to assigning a weight of 1 to both components of the objective function.

$$\sum_{j \in S/S'} \sum_{k \in K_j} z_{jk}\gamma_{jk} + \varphi \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk}\delta_t y_{jkt} \tag{13}$$

Table 6: Network upgrade with $C1$: maximum energy savings.

Scenario	Max Energy Savings vs. C_0^e	Max Energy Savings vs. C_{sleep}^e	Additional CapEx
S_60_30	-38.89%	**-6.38%**	+16.67%
S_100_50	-	-	-
S_120_60	-37.50%	**-9.10%**	+8.34%
S_180_80	-30.47%	**-23.05%**	+50.00%
S_220_100	-45.21%	**-5.73%**	+15.00%
S_250_120	-30.38%	**-5.20%**	+4.17%

– A new constraint is introduced to insure that the power consumption of the upgraded network is reduced by $1 - P$ percent with respect to the power consumption of the original topology C_0^e.

$$\sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk} h(t) y_{jkt} \leq P C_0^e \tag{14}$$

If a feasible solution is returned, the operator is able to meet the energy limitations by upgrading its network topology using only the candidate sites available at that moment. On the other hand, if no feasible solution is obtained, the imposed restrictions cannot be respected with the resources available to the network operator.

To simulate different market availabilities, we implement the upgrade phase of the test legacy networks in three different variations. We first assume that the same large $C1$ cells are the only device type accessible to the operator, who will have no choice but to try to meet the energy reduction constraints by installing new macro base stations. In better markets, $C2$ micro cells are also available, which are less expensive and more efficient in terms of CapEx and power consumed per unit of covered area. Finally, the last example considers the possibility to choose between three types of devices, including the most recent $C3$ pico cell technology which, in our examples, offers the highest connection quality and the minimum costs (CapEx and OpEx) per unit of capacity.

3.3.1 Macro Cell Upgrade

Let us consider first the case where only macro cells can be used to upgrade the legacy topologies. In Table 6 we gather the maximum energy savings that can be achieved by installing $C1$ base stations over the test scenarios' initial topologies. The percentages in the first column refer to the savings with respect to the original legacy network OpEx (C_0^e), while those on the second column display the savings calculated with respect to the managed version of the same legacy topology (C_{sleep}^e). Also, in the last column we report the additional capital expenses necessary for the upgrade. The results show that, when macro base stations only ($C1$) are accessible, network operators are hardly

Table 7: Network upgrade with $C1$ and $C2$: additional CapEx with approximately 70% energy reduction vs. C_0^e.

Scenario	Additional CapEx ($P = 30\%$)
S_60_30	+55.56%
S_100_50	+43.33%
S_120_60	+52.78%
S_180_80	+54.17%
S_220_100	+48.33%
S_250_120	+54.17%

able to improve their network power consumption situation. Excluding the most extreme values corresponding to scenarios S_100_50 and S_180_80, the average additional energy savings obtained with a $C1$ upgrade amount to only 5.28% of C^e_{sleep}, while the average extra installation costs equal 8.84% of the original CapEx C_0^c. In case of scenario S_100_50, adding new macro base station would not reduce the energy consumption any further than C^e_{sleep}. By consequence, while the energy management allowed as much as 40.42% decrease in the original OpEx, the network operator would not be able to meet energy caps limitations lower than such value. Scenario S_180_80 represents an isolated case with about 23% further decrease from C^e_{sleep}. As observed in the previous section and reported in Table 5, for this scenario the activation of a cell sleeping mechanism only allows 9.64% savings from the original C_0^e, by far the lowest value among the set of displayed results. When enhanced by additional $C1$ base stations, the legacy topology gains just enough flexibility to enable the largest savings measured in the network upgrade step. On the other hand, such energy efficiency improvement comes at the price of additional capital investments corresponding to 50% the initial CapEx C_0^c. Overall, we notice that energy cuts equal or greater than 40% to 45% of the initial OpEx C_0^e are out of reach with a $C1$ only topology upgrade. In other words, when macro base stations only are accessible, the network operator might not be able to comply with the thrusted regulations.

3.3.2 Macro and Micro Cell Upgrade

Differently from the case of $C1$ upgrade discussed above, network topologies upgraded with a mix of macro and micro cells show a great ability to adapt to imposed limitations. We tested several decreasing values of P, gradually augmenting the number of additional access stations and producing different network upgrade solutions according to the actual energy limitations. Judging excessively low energy caps not realistic, we decided to stop our analysis at $P = 30\%$; however, note that lower power consumption values could potentially be reached. Tables 7 displays the capital investments necessary to attain energy savings equal or greater than 70% of the original OpEx C_0^e, assuming that both $C1$ and $C2$ base station types are made available. The examples reported in the

Table 8: Network upgrade with $C1$, $C2$ and $C3$: energy savings vs. C_0^e, related additional CapEx and new access stations.

Scenario	Energy Savings	Additional CapEx	New BSs
S_60_30	-91.14%	+29.44%	0 $C1$, 4 $C2$, 13 $C3$
S_100_50	-79.67%	+24.00%	0 $C1$, 5 $C2$, 22 $C3$
S_120_60	-85.72%	+38.33%	0 $C1$, 39 $C2$, 0 $C3$
S_180_80	-83.27%	+42.29%	0 $C1$, 17 $C2$, 33 $C3$
S_220_100	-87.28%	+27.00%	0 $C1$, 10 $C2$, 62 $C3$
S_250_120	-77.71%	+35.28%	0 $C1$, 21 $C2$, 44 $C3$

table confirm that such energy reduction (typically only slightly larger than 70%) can be obtained by spending an amount corresponding to 45% to 55% of the initial C_0^c. The advantage in terms of adaptability is evident compared to the upgrade with macro cells only.

3.3.3 Macro, Micro and Pico Cell Upgrade

When not only macro and micro base stations are available to the operator at the moment of the network upgrade, but also pico cells, the results are even more striking. Table 8 reports the energy savings, additional capital investments and installed access stations resulting from a $C1$, $C2$ and $C3$ topology upgrade. Here, the value of P is set to be slightly lower that the maximum energy savings achievable through an energy-aware management of the legacy network. In this sense, the results in the table are obtained by setting the loosest value of P that could motivate the network upgrade. We observe that the most convenient solutions from the total expenses point of view feature highly energy-efficient upgraded topologies. While no additional macro cells are deployed, a large number of extra micro and pico cells allows most of the legacy base stations to be switched off during a great part of the day, thus dramatically decreasing the network power consumption. The additional expenditures on new equipment are non negligible, but the total costs are balanced by extremely low operational expenses. In other words, when the most modern technologies are within reach, it is in the operator's best interest to invest in a deep greening of its network regardless of the GHG emission caps imposed by the authorities.

4 What Impacts the Ability to Meet Energy Caps?

Intuitively, every topology would respond differently to enforced energy limitations. While we cannot exactly predict each network behavior, we are able to identify the major aspects that influence the ability of access networks to comply with energy caps.

Table 9: Outcome of cell sleeping mechanism on different legacy configurations.

	Legacy: $C1$		Legacy: $C1, C2, C3$	
	C_0^e	C_{sleep}^e	C_0^e	C_{sleep}^e
S_60_30	194 400	126 900 *(-34.72%)*	23 054	16 895 *(-26.72%)*
S_100_50	324 000	193 050 *(-40.42%)*	115 783	103 493 *(-10.62%)*
S_120_60	388 800	267 300 *(-31.25%)*	151 358	143 082 *(-5.47%)*
S_180_80	518 400	468 450 *(-9.64%)*	177 120	164 728 *(-7.00%)*
S_220_100	648 000	376 650 *(-41.88%)*	113 198	96 543 *(-14.70%)*
S_250_120	777 600	571 050 *(-26.56%)*	258 034	239 585 *(-7.15%)*

4.1 Composition of the Legacy Networks

In this paper, we rightfully assumed that legacy network topologies are characterized exclusively by macro cells. In Section 3.2 and Table 5 we observed that, when an energy-aware management is performed, such legacy networks show a good adaptability to energy caps. Depending on the single topology characteristics, energy reductions of 25% to 40% the original power consumption can be reached in most of the cases. Here we want to investigate the effect of the installation decisions made when the legacy network was initially deployed. In particular, we aim at answering the following question: Does a different initial topology composition (i.e., different cells' size) influence the effectiveness of the energy management mechanism? Or, in other words: How does a different legacy topology composition affect the cost of complying with the energy requirements?

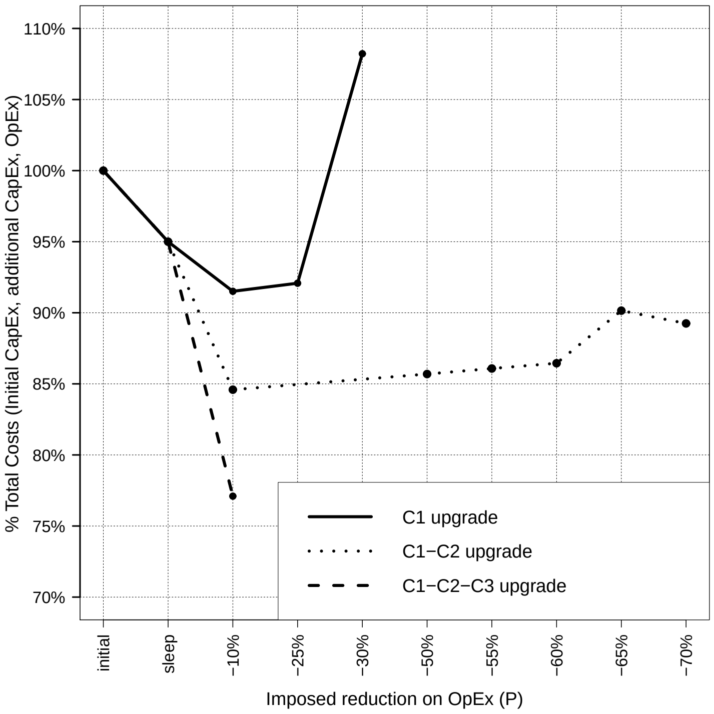
Let us assume for a moment that our legacy networks were not limited to $C1$ base station configurations, but deployed also more modern cell technology as $C2$ and $C3$. This example could reproduce the case of a network operator that recently deployed or remodeled its cellular network. Some interesting results are gathered in Table 9, which reports for every scenario the OpEx of unmanaged and managed legacy networks (C_0^e and C_{sleep}^e, respectively), in case the legacy topology deploys only macro cells ($C1$) or also micro and pico cells ($C1, C2, C3$). The percentages next to the C_{sleep}^e values clearly show the larger energy consumption reductions in macro cell networks. Having available different cell sizes, minimum CapEx heterogeneous topologies are able to better focus the coverage capabilities in those areas where the highest traffic is offered. The initial operation costs, as well as the capital ones, are much lower with respect to the macro cell legacy network values. On the other hand, the higher network efficiency translates in a decreased level of over-provisioning, which in turns prevents the cell sleeping mechanism to reach significant energy savings, averaging at around 12%.

Such contrast has an important monetary impact on operators owning heterogeneous networks who need to meet certain energy requirements. While they are able to save a considerable amount of energy and money during regular operation, they may be forced to resort to a network upgrade, thus investing capital, much more frequently than less "virtuous" macro cell network operators. As an example, considering the energy cap to be set at 30% of the consumption value at business-as-usual operation C_0^e, we notice that only in two scenarios (S_180_80 and S_250_120) macro cell network operators would need to lay out capital in upgrading their topology. Conversely, no heterogeneous network operator could rely on an energy-aware management to reach the power reduction targets.

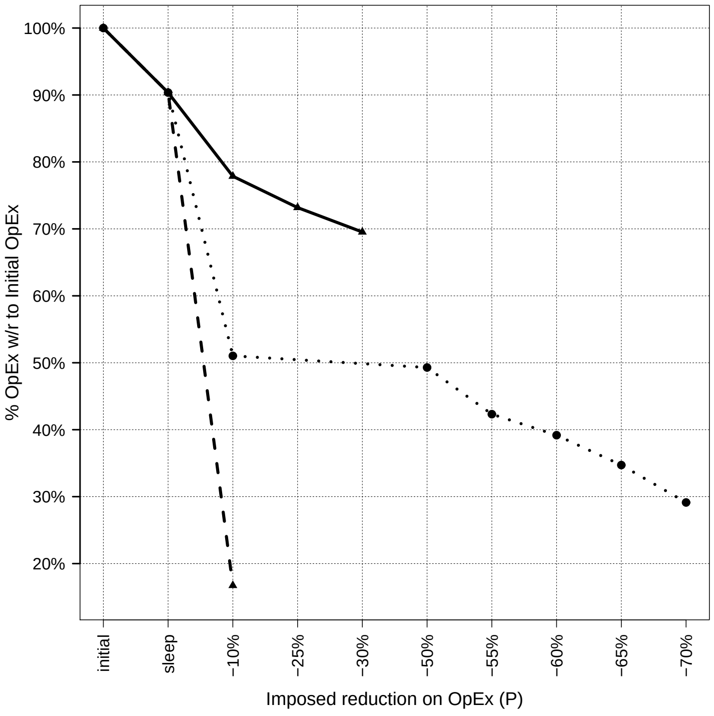
4.2 Network Upgrade and Technology Availability

The cell types chosen at the moment of the initial network installation is not the only factor that impacts the network adaptability. In Section 3.3 we showed how an operator having macro, micro and pico cells at its disposal in the network update phase can achieve very low energy consumptions with a relatively small effort in terms of capital costs. Upgrades performed with macro and micro cells represent a slightly less favorable example. In this case, a network operator is able to achieve any energy restriction with the available base station categories; however, the capital cost of reaching the emission target would be generally higher, especially when very tight limitations (i.e., low values of P) are applied. On the other hand, a network operator using only macro base stations to upgrade its topology would likely fail to comply with the energy caps.

The imbalance in the network adaptation capabilities highlights an intrinsic unfairness of the carbon cap system, which indiscriminately applies to every involved network operator, regardless of topology characteristics and accessible devices. Figures 1 and 2 provide a representation of the different levels of adaptability offered by the market availability at the network upgrade stages. The pictures illustrates two of the six scenarios, S_180_180 and S_220_100 respectively, but similar results were obtained for all the tested instances. In Figures 1a and 2a the percentage variations of the total costs (C_0^c, C_0^e and additional CapEx) are depicted, while Figures 1b and 2b report the percentage variations of the operation expenses when increasingly tight energy caps are imposed. The leftmost point on every graph is set at 100%, representing the reference legacy topology. The points in correspondence of the "sleep" label denote the values found by applying a cell sleeping mechanism on the initial topology. The following points refer to network upgrades with increasingly tighter OpEx reduction constraints. Bold lines show results corresponding to networks that can be upgraded with macro cells only. When also micro cells are available, dotted lines are used, while dashed lines illustrate the case of networks upgraded with macro, micro and pico cells. Note that the first segment (i.e., from "initial" to "sleep"), not involving any network upgrade, is common to the three cases. Also note that, in the first figure, the higher value of total costs at -65% ($P = 35\%$) with respect to the one at -70% ($P = 30\%$) is explained by the higher accepted optimization gap.

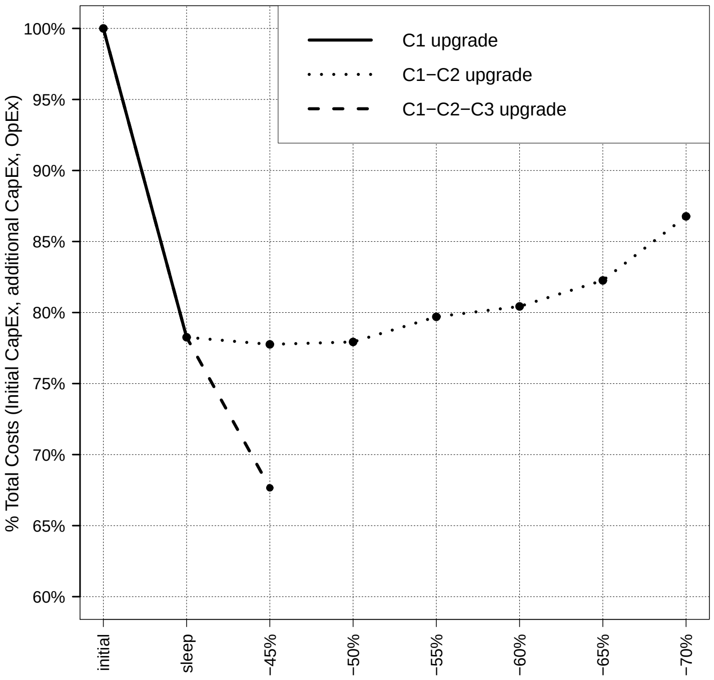


(a) *Total cost vs. imposed energy caps.*

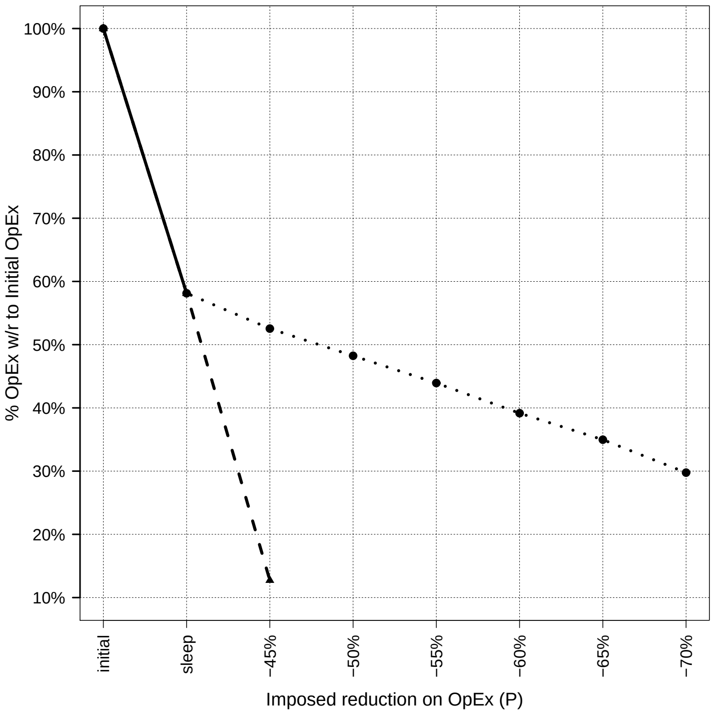


(b) *OpEx vs. imposed energy caps.*

Fig. 1: Total cost and OpEx variations when power consumption reduction actions are taken, scenario S_180_180.



(a) *Total cost vs. imposed energy caps.*



(b) *OpEx vs. imposed energy caps.*

Fig. 2: Total cost and OpEx variations when power consumption reduction actions are taken, scenario S_220_100.

Observe first the bold lines in pictures Figure 1a, representing a macro cell upgrade performed on a legacy network in scenario S_180_180. Imagine that the energy caps are set at -25% of the original OpEx ($P = 75\%$). In this case, a successful $C1$ upgrade will be fairly cheap, possible by spending an amount corresponding to the 12.5% of C_0^c. Considering the extra capital investments and the lower OpEx, the total costs decrease to about 92% the initial value. Now assume that the energy caps are slightly tighter, set at -30% of C_0^e ($P = 70\%$). Achieving this target is still doable with macro base stations only; however, a seemingly small extra 5% decrease in power consumption bumps the total expenses up at about 108% the legacy value, due to additional CapEx corresponding to as much as 50% of C_0^c. Looking now at Figure 2a, you can see that an operator in scenario S_220_100 would be able to meet energy caps set at 40% of C_0^e by only performing energy management on its network. On the other hand, installing new macro devices would not guarantee any lower power consumption.

The disadvantage of markets where only large cells are available is clear when we focus on dashed and dotted lines. Micro and pico cells allow network operators in both scenarios to achieve any power reduction at a reasonable price. Intermediate energy caps, limiting the OpEx between -40% to -50% of the initial value C_0^e, correspond to the lowest value of total costs for upgrades with $C1$ and $C2$ base stations. In other words, the additional capital expenses are balanced by the energy savings in the most favorable way for network operators. As indicated by the concave shape of the overall costs line, tighter consumption restrictions can be achieved only with higher capital investments which are only partially repaid by power savings. In any case, the overall costs do not exceed 85% to 90% of the original sum of CapEx and OpEx. The lowest total expenditures and energy consumptions are effortlessly reached by allowing pico base stations in addition to macro and micro cells to improve the legacy topology. As displayed in both figures, operators having at their disposal the most recent cell technology can reduce their power consumption by at least 80% to 90%, still decreasing their total expenses of about 23% and 32% with respect to $C_0^c + C_0^e$. In light of these considerations, we can deduce that the market availability at the moment of the upgrade is fundamental in determining the ability of the network operator to comply with the agreed energy caps. In particular, the accessible cell technology directly impacts the investments necessary to meet the target set by the authority.

5 How Can Energy Caps Be Implemented Fairly?

As we emphasized throughout this paper, network topologies with different characteristics show different ability to adapt to energy consumption regulations. We showed that the composition of the legacy topology in terms of deployed cells impacts the potential power savings achieved by an energy-aware mechanism. Thus, despite their much higher initial OpEx, macro cell networks perform better than heterogeneous ones when network operation is performed.

Moreover, while newest small cell technologies simplify the achievement of low power usage through network upgrade, the availability of only older, larger cells represents an obstacle for network operators who need to meet specific targets. The particular situation where operators are subjected to limited technology availability highlights the need of an intermediary entity or system, created to insure a certain level of fairness among the involved parties.

In this sense, carbon markets play a primary role in the context of energy consumption regulation. Emission trading schemes (ETS) represent one of many market-based mechanisms. Once a certain cap is set on the amount of produced GHGs, emission allowances (or credits) are distributed amongst the participating companies. Members can trade allowances with one another as needed, as well as buy a certain number of credits from emission reduction projects around the world. At prearranged times, participating companies must turn in to the authorities enough allowances to cover their GHG emissions. Companies that managed to reduce their emissions can save the extra allowances for the year to come or sell them to other companies in need. Without carbon markets, every network operator unable to reach the agreed target would incur heavy fines by the regulatory entity. Instead, emission trading schemes allow operators to compensate for their high emissions by buying carbon credits from more virtuous participants, which in turn will be rewarded with extra income for their energy reduction efforts.

Carbon markets represent a further incentive for operators having full market availability to exploit small cells and maximize their energy savings, regardless of the imposed targets. In fact, operators that upgrade their topology using small cells could not only enable remarkable yearly energy savings but, in a carbon market context, they would be able to save carbon credits and sell them to other operators for extra income. On the other hand, network operators using only macro base stations that are unable to decrease their power consumption to the agreed levels could resort to the purchase of carbon credits to avoid penalties from the regulatory entity.

6 Conclusion

In this paper we used a previously defined framework for the joint planning and energy management (JPEM) of mobile systems to try to find an answer to three fundamental questions that network operators could ask when facing energy consumption restrictions. To the question of how can an operator meet energy caps, we proposed two solutions: managing its network or improving it by installing new access devices. The JPEM framework allows to assess the savings when energy management is carried on on both legacy and upgraded network topologies. For the cases we examined, we found that those legacy networks constituted exclusively by macro cells ($C1$) can easily reach 25% to 40% energy savings just by means of an energy management mechanism. When upgrades are considered we found that, when there is more diversity in the access equipment, the best trade-off between energy savings and additional costs can be achieved. To the question of what influences the ability of a network to meet energy caps, we observed the crucial role played by the type of legacy base stations as well as by the technology availability for network upgrades. In general, good players that have already a quite efficient network will be disadvantaged in complying with the energy caps. Due to the importance of both legacy and upgrade technology in determining the network energy usage, it is possible that some operators would not be able to reduce their consumption to meet the imposed targets. Therefore, we showed that the only way to implement energy caps in a fair way is to allow those operators to play in carbon markets.

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