Radio Planning of Energy-Efficient Cellular Networks

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***Abstract*—We introduce a novel approach that jointly optimizes planning and management for cellular networks, aiming at limiting the energy expenses while guaranteeing QoS and minimizing operators capital expenses. Results from LTE test networks confirm that an effective energy-efficient operation depends on the planning decisions and show that power savings of up to 54% can be obtained with modest increases in initial investments.**

I. Introduction

Green networking has become one of the most important topics in ICT in general and in wireless access networks in particular, because of their high power requirements. A thorough report on wireless energy consumption issues can be found in [1], while good surveys on the most remarkable techniques toward green mobile networks are provided by [2], [3]. Focusing on cellular networks, up to now the literature has dealt with green network planning *or* network energy management, being the two phases always addressed as separate problems.

Concerning energy management, the possibility of switching off some nodes given the network topology and a fixed traffic demand is evaluated in [4], with the aim of minimizing the total power consumption while respecting QoS constraints. Deterministic traffic variations over time are taken into account in [5], where the authors characterize the energy saved by reducing the number of active access devices for different cell topologies, while in [6] a random traffic distribution is considered and the number of active Base Stations (BSs) is dynamically minimized to meet the traffic variations in both space and time dimensions. An optimization approach for dynamically managing the energy consumption of wireless networks switching on and off access stations in different periods of time is proposed in [7].

Regarding network planning, authors in [8] account for spatial traffic variations by dividing the service regions into dense and sparse zones and proposing an "adaptive" deploying strategy where the size of the cells can be adjusted according to real users request. The cells layout influence on power consumption is investigated in [9] where the authors demonstrate, by varying the number of micro BSs per-cell in addition to conventional macro sites, that the use of micro BSs has a limited effect on the energy expenses. On the other hand, in order to upgrade the network capacity in a cost-effective way, in [10] a two-stage greedy procedure is proposed for deploying micro cells overlapping a pre-existing network: the first step aims at installing additional micro BSs over a previously deployed macro BSs layer for satisfying the peak demand, while the next one tries to manage the network operation to reduce power waste during low traffic periods.

Differently from the aforementioned papers, we tackle the problem from an innovative point of view claiming that, for the operation to be really power-efficient, networks have to be designed taking into account the next energy-aware management. We do not assume a pre-existing infrastructure but rather find *the best topology from the energy consumption point of view*, optimizing in a joint way the network planning (involving BSs location and cells dimension) and the energy-efficient operation according to the varying traffic demand. The resulting network topologies reveal themselves as extremely flexible, deploying micro as well as some macro cells, demonstrating that an effective energy-efficient operation strongly depends on the network coverage structure and on the radio planning decisions taken during the design phase.

The remainder of the paper is organized as follows. Relevant issues for energy-efficient wireless network design and management are discussed in Section II, where the proposed joint model is also presented. The numerical results are discussed in Section III. Finally, Section IV summarizes the entailed information while proposing ideas for further exploration.

II. Cellular Networks Model

Traditionally, planning a wireless access network roughly deals with finding positions and configuration settings for network devices while matching service requirements (including budgetary ones). Examples for 2G, 3G and Wireless LANs hot spots can be found in [11], [12] and [13], respectively. A common approach to the coverage optimization problem resorts to discrete mathematical programming models [14]. A set of Test Points (TPs), which represent traffic centroids requesting a given amount of traffic, is identified in the service area. Instead of allowing the positioning of BSs anywhere in the area, a set of Candidate Sites (CSs), where the BSs can be installed, is defined. Since we can evaluate (or even measure in the field) the signal propagation between any pair of TP and CS, the subset of TPs covered by a sufficiently strong signal is assumed to be known for a BS installed in any CS. The coverage problem results in the classical minimum cost set covering problem. On the other hand, given a physical network topology as well as the average traffic profile characterizing each considered time period, an energy-aware network operation aims at switching off as much cells as possible during low traffic hours for minimizing the power expenditures, always assuring the complete area coverage and the transmission quality constraints.

The joint approach we propose originates from the idea that, when power management is considered, the level of flexibility offered by the network topology is essential for adapting the capacity of the cellular system to the varying traffic load by switching on and off some BSs. Conversely, since network planning is usually optimized so as to minimize mobile operators' Capital Expenditure (Capex), a two-step approach which tries to efficiently manage a previously designed, minimum cost topology network will lead to modest energy savings. Therefore, if the objective is that of obtaining an *effective energy-aware operation*, the power management *must* be considered when planning the radio coverage of the cellular network. Thus, starting from the radio planning model described above, we make some fundamental modifications: not only we refine variables and constraints to allow the power management mechanism to turn off some stations when not needed, but we also include in the objective function the Operational Expenditure (Opex), assuming that their variable part is mainly due to the energy cost. In order to prove our claims, we tested our model on Long Term Evolution (LTE) technology scenarios. In what follows, we briefly expose and discuss the traffic variation in time, the different kind of BSs and the propagation model considered in our framework. Then, our joint framework is introduced and described.

A. Traffic Variation Pattern

To generate realistic instances, we defined a daily traffic pattern based on the downlink traffic measurements presented in [15], which reflect mobile users habits and state the active users percentages in different time intervals. Let $T = [t_1, t_2, \ldots, t_8]$ be the ordered set of time intervals. Table I provides the name of the specific interval, the span of time it represents and the value of normalized traffic.

To comply with the outlined traffic profile, for each TP (from now on called *Traffic* TP) we generated a random value uniformly chosen between 20 and 40 Mb/s and a random number in the [0,1] interval, associated with every time period. The first value denotes the traffic amount provided by the Traffic TP to the network during period t only if the second number is less or equal the normalized traffic value in $t \in T$. Furthermore, in our modeling framework we introduced *Coverage* TPs which, differently from Traffic ones, do not produce any traffic. However, since they are disposed on a regular grid overlaying the service area, they are essential to ensure the total coverage in the dimensioning phase even in the off traffic regions.

TABLE I
TRAFFIC PROFILE IN THE DIFFERENT TIME PERIODS.

Interval	Start	End	Normalized Traffic
t_1	0 am	2 am	0.8
t_2	2 am	4 am	0.55
t_3	4 am	8 am	0.25
t_4	8 am	10 am	0.45
t_5	10 am	1 pm	0.65
t_6	1 pm	6 pm	0.8
t_7	6 pm	8 pm	0.9
t_8	8 pm	12pm	1

TABLE II
BSS CHARACTERISTICS.

	C1	**C2**	**C3**
Installation cost (k€)	30	10	1
Transmitted Power (W)	19.9	6.3	0.1
Consumed Power (W)	1350	144.6	14.7
Capacity (Mb/s)	210	70	70
Coverage Radius (m)	1230	850	241

B. Base Stations Categories

As we asserted the importance of having network *flexibility* for an effective energy-efficient operation, we allowed the possibility of installing three BSs types (called here *configurations*), having different installation cost, capacity and transmitted power. Also, to enable the power management mechanism, every BS can be switched off and enter in the stand-by mode in case of very low traffic profile. Table II gathers realistic transmitted and consumed power, as well as capacity values for LTE BSs, extracted from [15]. The consumed power, in particular, represents the mean equipment power consumption (including power amplifier, signal generator, air conditioning and microwave link). Note that the proposed design approach is general and can be used with any mix of BSs types and technologies.

C. Propagation Model

In real scenarios, deterioration of transmitted signal quality is commonly assumed to be due to path loss, slow fading or shadowing and fast fading. A frequent assumption in network design modeling is not to include shadowing, while fast fading was neglected because of the characteristics of our problem (small-scale variations are fairly rapid in space).

For our experiments, we calculated the median path loss using the COST-231 Hata model [16]:

$$\begin{aligned}\overline{PL}(d) = 46.3 + 33.9log_{10}(f) - 13.82Log(h_b) - a(h_r) \\ + (44.9 - 6.55Log(h_b))Log(d) + c_m.\end{aligned} \quad (1)$$

Here, f denotes the operating frequency (2600 MHz) while h_b (assuming values 12 m, 10 m or 8 m according to the BS configuration) and h_r (set to 1.5 m) are the correction factors for BS and user antennas height. For suburban areas, the parameter c_m is equal to zero and the function $a(h_r)$ is defined as follows:

$$a(h_r) = (1.1log_{10}f - 0.7)h_r - (1.56log_{10}f - 0.8). \quad (2)$$

Moreover, we assume antenna gains being 15 dB ($C1$ and $C2$) and 12 dB ($C3$) while cable losses are equal to 2 dB.

D. Energy-Aware Radio Planning

The following parameters and variables are given.

Parameters

I_c: Set of Coverage TPs, which do not generate any traffic,
I_t: Set of Traffic TPs,
S: Set of available CSs to locate BSs,
K_j: Set of possible configurations for a BS in $j \in S$,
δ_t: Duration of 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 in $j \in S$ with configuration $k \in K_j$,
γ_{jk}: Installation cost for a BS in $j \in S$ with configuration $k \in K_j$,
ϵ_{jk}: Power consumption for a BS in $j \in S$ with configuration $k \in K_j$,
r_{ij}: Distance between the TP $i \in I_t$ and a BS in $j \in S$,
β, ϑ: Trade-off parameters in the objective function,
a_{ijk}: Coverage binary parameter equal to 1 if TP $i \in I_c \cup I_t$ is covered by a BS in $j \in S$ with configuration $k \in K_j$.

Binary variables

z_{jk}: equal to 1 if a BS is installed in $j \in S$ with configuration $k \in K_j$,
y_{jkt}: equal to 1 if a BS in $j \in S$ with configuration $k \in K_j$ is active in period $t \in T$,
x_{ijt}: equal to 1 if TP $i \in I_t$ is assigned to BS in $j \in S$ in period $t \in T$.

The aim of the following formulation is minimizing the sum of Capex and Opex expenses by deploying a convenient topology from the energy consumption standpoint and managing the access devices while guaranteeing coverage and QoS constraints.

$$\min \quad \sum_{j \in S} \sum_{k \in K_j} z_{jk}\gamma_{jk} + \beta \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jkl}\delta_t y_{jkt} + $$

$$+\vartheta \sum_{i \in I_t} \sum_{j \in S} \sum_{t \in T} x_{ijt}\delta_t r_{ij} \quad (3)$$

$$\text{s.t.} \quad \sum_{j \in S} \sum_{k \in K_j} a_{ijk} y_{jkt} \geq 1, \forall i \in I_c \cup I_t, t \in T \quad (4)$$

$$x_{ijt} \leq \sum_{k \in K_j} a_{ijk} y_{jkt}, \forall i \in I_t, j \in S, t \in T \quad (5)$$

$$\sum_{i \in I_t} x_{ijt} p_{it} \leq \sum_{k \in K_j} c_{jk} y_{jkt}, \forall j \in S, t \in T \quad (6)$$

$$\sum_{j \in S} x_{ijt} = 1, \forall i \in I_t, t \in T \quad (7)$$

$$y_{jkt} \leq z_{jk}, \forall j \in S, k \in K_j, t \in T \quad (8)$$

$$\sum_{k \in K_j} z_{jk} \leq 1, \forall j \in S \quad (9)$$

$$z_{jk}, y_{jkt}, x_{ijt} \in \{0, 1\}, \forall j \in S, k \in K_j \quad (10)$$

The objective function (3) is composed of the Capex term that accounts for the equipment installation cost, the Opex term that considers energy expenses in the operational setting and a final term which induces the model to assign every Traffic TP to the nearest available BS to guarantee a better connection quality between users and antennas. The trade-off between the three terms is adjusted by playing with the weight parameters β and ϑ. We tested very different values of β, while ϑ varies proportionately according to β. When installation expenses are the only cost to be minimized, β is set to 0: this way, the Opex term is excluded from the objective function and the resulting network will deploy a minimum cost topology. Setting the value of β to higher values enables the energy management mechanism and forces the model to reduce not only capital but also operational costs by introducing the Opex term in the objective function.

There are two types of *coverage constraints.* Constraints (4) provide a minimal and constant coverage by ensuring that all the TPs are within the service area of at least one installed BS, while (5) ensure that Traffic TPs are only assigned to a BS they are covered by. Since they do not provide any traffic, Coverage TPs are not directly assigned to a specific BS. *Capacity constraints* (6) guarantee that each active BS can satisfy the traffic demand of the covered Traffic TPs and *assignment constraints* (7) force every Traffic TP to be assigned to only one BS. (8) are *linking constraints* between variables y and z, while *configuration constraints* (9) impose that at most one configuration is chosen for every CS. Finally, (10) impose the binary values for the decision variables. The proposed model, which is a linear binary problem, is NP-hard.

III. Experimental Results

A. Resolution Approach

The mathematical model illustrated in Section II-D was implemented on AMPL and solved with CPLEX branch and bound solver [17], which produced optimality gaps below 1.5% for the tested instances. To assess the effectiveness of our framework, we needed to generate realistic LTE cellular networks instances so that the numbers of CSs and Traffic TPs are similar to the ones that can be found in real networks. Therefore, an Instance Generator (IG) was designed, implemented in C++ and used as an input for the CPLEX solver. With the help of the IG, we created a small and a bigger scenario. *Scenario nr.1* allows 40 CSs, 121 Coverage TPs and 30 Traffic TPs over a square area of $4\,km^2$, while *Scenario nr.2* has a square area of $25\,km^2$ and 60 CSs, 676 Coverage TPs and 60 Traffic TPs.

As already said, for every scenario we tested several values of trade-off parameters β and ϑ. In order to provide a fair evaluation of the proposed model, we needed to compare our results with the ones that can be obtained by separately optimizing, first, the network design, and then, the network management. This approach is comparable to the one adopted in [10] for deploying an additional layer of BSs to improve the network capacity; however, instead of exploiting a greedy heuristic, we adapted our model to reproduce and solve to optimality the mentioned method in the following steps:

1) Run the joint optimization model with $\beta = 0$, so that no energy management is enabled and the minimum cost topology is chosen;
2) Fix variables z_{jk} according to the results of the previous step: installed BS variables are set to 1. This will fix locations and characteristics of installed BSs;
3) Run the joint model where z_{jk} are no longer variables but parameters set according to step 2 (network topology is already defined) and the Capex term is excluded by the objective function.

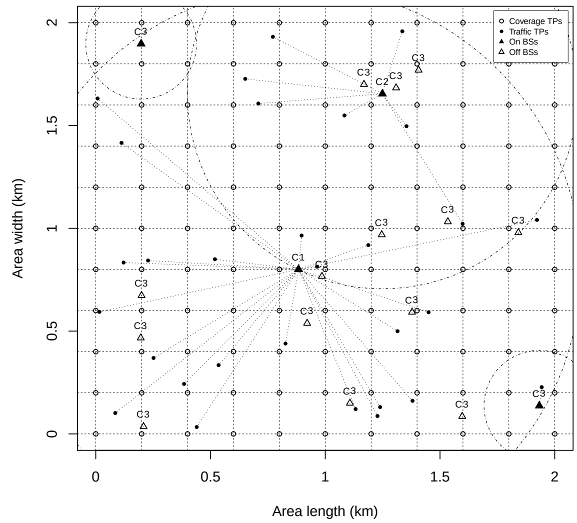
In the next Section, as well as in figures and tables, we will refer to this approach with the name *two-step*, in opposition to the proposed *joint* method.

B. Numerical Examples

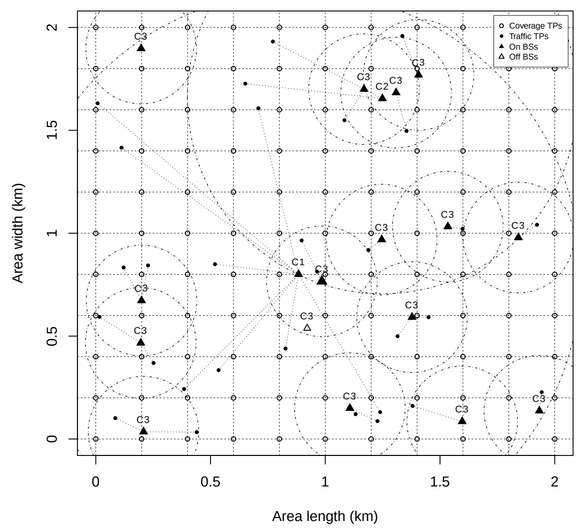
In what follows we will focus on figures representing results for the small scenario to have a better and easy understanding on the outcome of the suggested approach. In every picture, Traffic TPs are represented as black dots while Coverage TPs are white dots, arranged on a regular grid every 200 m. Only selected CSs are depicted: switched off BSs are symbolized by white triangles, while switched on ones are represented by black triangles. Finally, dashed circumferences mark out the coverage radius of every turned on BS and dotted lines link Traffic TPs with the BS they are assigned to.

Let us concentrate on Figure 1, where we present pictures of the network provided by the two-step approach. Since in the network planning step only Capex costs are minimized, the minimum cost network topology is deployed. Looking at Figure 1a, which displays the lowest traffic time period, we note that 2 BSs, one of type $C1$ and one of type $C2$, cover almost the entire area. As a matter of fact, big cells are suitable especially to guarantee a basic coverage in low traffic zones, where mainly Coverage TPs are located. However, since the traffic provided by Traffic TPs is pretty high if compared to BSs capacity, other BSs are needed to fully serve the users demand (Figure 1b, representing the peak traffic period). For this reason, the optimal solution includes also 16 BSs of type $C3$ in addition to the bigger ones. The installation cost deriving from the small cells corresponds to 16000 €, which appears to be the most convenient choice from the Capex standpoint (compared to at least 90000 € that would be necessary to deploying nine additional $C2$ or three $C1$ BSs to serve the same amount of traffic).

The outcome of the joint design and management approach applied to Scenario nr.1 can be appreciated in Figure 2. The second picture (Figure 2b) represents the network topology in the peak traffic time period t_8 when $\beta = 10$. With respect to the case of $\beta = 0$ described above, we note that now 21 BSs instead of 18 have been installed,



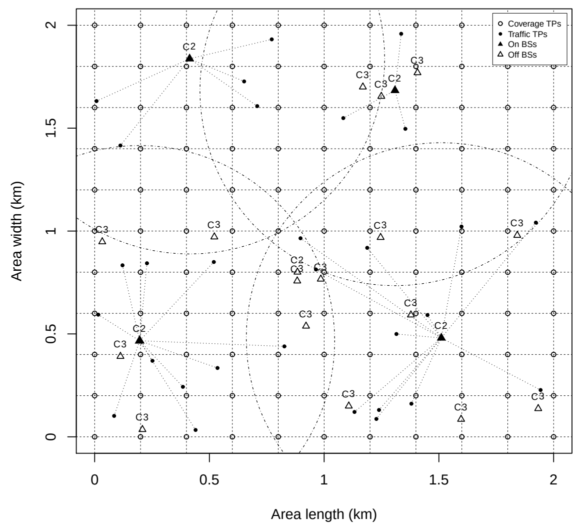
(a) $\beta = 0$, t_3: *18 BSs installed, 4 BSs on.*



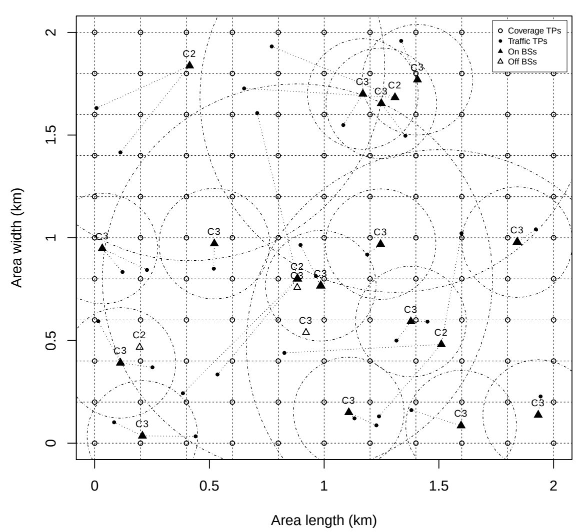
(b) $\beta = 0$, t_8: *18 BSs installed, 17 BSs on.*

Fig. 1. Significant topologies obtained for Scenario nr.1 using the two-step approach.

providing 16% of Capex increase (equivalent to 10000 €, see Table III). Most are pico cells (16 of type $C3$), 5 type $C2$ BSs ensure a complete coverage and no macro BSs are installed. Note that, despite the energy management mechanism behaves similarly in both approaches, the joint model allows greater energy savings. In fact the macro BS deployed for $\beta = 0$, providing wide area coverage but having high power requirement, is replaced with 4 $C2$ BSs, which spend a lower amount of energy for every unit of traffic served. Also note that, although we are analyzing the maximum traffic time period, 2 type $C3$ and 1 type



(a) $\beta = 10$, t_3: *21 BSs installed, 4 BSs on.*



(b) $\beta = 10$, t_8: *21 BSs installed, 18 BSs on.*

Fig. 2. Significant topologies obtained for Scenario nr.1 using the joint approach.

$C2$ BSs are turned off. This fact further underlines the influence of the joint model, which privileges the operation effectiveness on the capital savings with growing values of β . Observing now Figure 2a, we can see the behavior of the same network ($\beta = 10$) during the lowest traffic period t_3. The energy management mechanism allows to switch off as much as 17 BSs, since only 4 type $C2$ BSs are able to provide the complete coverage of the service area. Thus, energy savings of 52% with respect to the two-step network can be reached, corresponding to more than 1500 € saved every year (see Table III).

The main results obtained solving Scenario nr.1 and Scenario nr.2 with different values of β are presented in Tables III and IV respectively. For each scenario, the following values are reported: 1) Time required by CPLEX for solving the optimization problem; 2) Installation costs (Capex), expressed in Euro and corresponding to the value of the first component of the objective function; 3) Total amount of energy required in a day by the deployed network, measured in kiloWatt hour and given by the second part of the objective function divided by $\beta \cdot 1000$; 4) Daily running expenses for the whole network, based on the Italian energy cost for business users of 0.2 € per kiloWatt hour; 5) Number and types of BSs installed in the analyzed area; 6) Number and types of BSs powered on in each time period. The percentages in brackets refer to the two-step case.

We observe that varying the value of β, the installation costs grow while the total energy consumed decreases. In particular, note that just enabling the joint optimization of network design and energy management by setting $\beta = 1$ induces a non-negligible increase in Capex (11% for Scenario nr.1 and 5% for Scenario nr.2) and a different topology than for the case of minimum cost network planning. This result is not straightforward since, for such a small value of β, the Capex term still overfills the Opex one in the objective function. If we focus now on Scenario nr.2, the Capex increase is 12% with $\beta = 10$ while energy demand decreases 42% compared to the two-step case. Taking this case as example, it is possible to calculate that the additional initial investment (corresponding to 30000 €) is recovered in less than five years of network operation, since the energy savings correspond to 6099 € spared every year. Here, the value of $\beta = 10$ appears a good compromise between installation costs and energy consumption. Increasing β further provides no improvement in energy saving at the price of remarkable additional Capex expenses. Obviously, in general, the most appropriate value of β depends on many issues including the characteristics of the problem instance and BSs types. Therefore, an analysis of the Pareto optimal solutions with different values of β allows the network designer to select the best option according to the network development policies of the mobile operator.

IV. Conclusion

One of the main instruments available to mobile operators to save energy and reduce operational costs is that of dynamically managing the network to switch BSs on and off and adjust their emission power according to the traffic variations. The optimization framework we have proposed in this paper starts from the belief that, for the power management to be efficient, networks have to be *designed* taking into account operational energy management. Therefore, we have formulated a mathematical model that selects the BSs to be installed and jointly applies the energy management strategy to the deployed

TABLE III

Some results from Scenario nr.1 with different values of β.

Scenario nr.1

	$\beta = 0$ $\vartheta = 0.0001$ (two-step)	$\beta = 1$ $\vartheta = 0.001$ (joint)	$\beta = 10$ $\vartheta = 0.01$ (joint)
Computation Time	1 sec	1h 4min	21min
Capex (k€)	56	62 *(+11%)*	66 *(+16%)*
Energy (kWh/d)	39.76	19.24	18.14
Opex (€/d)	7.95	3.83 ***(-52%)***	3.63 ***(-54%)***
Installed BSs	18	17	21
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 5
	C3 - 16	C3 - 12	C3 - 16
Active BSs: t_1	16	17	17
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 5
	C3 - 14	C3 - 12	C3 - 12
Active BSs: t_2	9	11	10
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 4	C2 - 4
	C3 - 7	C3 - 7	C3 - 6
Active BSs: t_3	4	5	4
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 4	C2 - 4
	C3 - 2	C3 - 0	C3 - 0
Active BSs: t_4	8	12	11
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 4	C2 - 4
	C3 - 6	C3 - 8	C3 - 7
Active BSs: t_5	14	16	15
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 5
	C3 - 12	C3 - 11	C3 - 10
Active BSs: t_6	14	15	15
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 4
	C3 - 12	C3 - 10	C3 - 11
Active BSs: t_7	16	16	16
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 4
	C3 - 14	C3 - 11	C3 - 12
Active BSs: t_8	17	17	18
	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 4
	C3 - 15	C3 - 12	C3 - 14

TABLE IV

Some results from Scenario nr.2 with different values of β.

Scenario nr.2

	$\beta = 0$ $\vartheta = 0.0001$ (two-step)	$\beta = 1$ $\vartheta = 0.001$ (joint)	$\beta = 10$ $\vartheta = 0.01$ (joint)
Computation Time	1sec	15min	9sec
Capex (k€)	259	271 *(+5%)*	289 *(+12%)*
Energy (kWh/d)	198.22	132.32	114.60
Opex (€/d)	39.64	26.46 ***(-33%)***	22.93 ***(-42%)***
Installed BSs	24	33	33
	C1 - 5	C1 - 2	C1 - 2
	C2 - 10	C2 - 20	C2 - 22
	C3 - 9	C3 - 11	C3 - 9
Active BSs: t_1	17	27	29
	C1 - 5	C1 - 2	C1 - 1
	C2 - 10	C2 - 20	C2 - 21
	C3 - 2	C3 - 5	C3 - 7
Active BSs: t_2	16	23	22
	C1 - 5	C1 - 2	C1 - 1
	C2 - 10	C2 - 19	C2 - 20
	C3 - 1	C3 - 2	C3 - 1
Active BSs: t_3	17	23	22
	C1 - 5	C1 - 2	C1 - 1
	C2 - 9	C2 - 18	C2 - 20
	C3 - 2	C3 - 3	C3 - 1
Active BSs: t_4	16	22	22
	C1 - 5	C1 - 2	C1 - 1
	C2 - 10	C2 - 18	C2 - 20
	C3 - 1	C3 - 2	C3 - 1
Active BSs: t_5	17	24	25
	C1 - 5	C1 - 2	C1 - 1
	C2 - 10	C2 - 18	C2 - 21
	C3 - 2	C3 - 4	C3 - 3
Active BSs: t_6	18	29	30
	C1 - 5	C1 - 2	C1 - 1
	C2 - 10	C2 - 18	C2 - 22
	C3 - 3	C3 - 9	C3 - 7
Active BSs: t_7	21	30	29
	C1 - 5	C1 - 2	C1 - 2
	C2 - 10	C2 - 20	C2 - 22
	C3 - 6	C3 - 8	C3 - 5
Active BSs: t_8	24	33	33
	C1 - 5	C1 - 2	C1 - 2
	C2 - 10	C2 - 20	C2 - 20
	C3 - 9	C3 - 11	C3 - 9

network. Our goal is not only to minimize the sum of installation and operational costs, but also finding the best trade-off between keeping low capital investments and reducing energy consumption. Future work will consider heuristic methods to solve larger test instances.

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