Radio Planning of Energy-Aware Cellular Networks

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Abstract

This paper introduces a joint planning and management optimization approach for cellular networks to limit energy consumption while guaranteeing QoS and minimizing operators Capex and Opex. The modeling framework shows that an effective energy-efficient operation depends on the planning decisions. Conversely, it also shows that planning with energy management operation in view yields more versatile topologies than more traditional models based only on Capex. Results for LTE networks are provided and show that savings up to 65% in energy expenses are possible with slight increases in capital investments.

Keywords: Energy Efficiency, Cellular Networks, Wireless Network Planning, Network Operation, Green Networking, Joint Planning and Energy Management, Network Design.

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1. Introduction

It has been reported [1] that the ICT sector is responsible for the world energy expenditures for a percentage that ranges from 2% to 10%. Of particular concern is the consumption of the cellular wireless system, both for its increasing pervasiveness that pushes for more wireless infrastructure and for the well known fact that Base Stations (BSs) are particularly energy-hungry, representing over 80% of the power used in the radio segment.

While responsibility for climate change is the main push for green networking research, network operators are equally interested in energy consumption reduction for economic reasons. Two types of cost are incurred: Capital Expenditures (*Capex*), related to the purchase and installation of

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radio equipment, and Operational and Management Expenditures (*Opex*), consisting on energy, site rentals, marketing and maintenance costs [2]. The challenge in terms of energy-aware modeling is to convey both types of cost and power issues into a single modeling framework, which is precisely the objective of this paper. The only example of energy-aware joint design and management method is presented in our recent work [3], where we introduced a similar approach for mesh networks and provided multiple examples and model variations for supporting our thesis. However, to the best of our knowledge, the problem has never been tackled from the cellular network point of view.

The article is divided as follows. In Section 2 the modeling framework philosophy is introduced, while Section 3 reports general as well as wireless green networking literature. The propagation model, the traffic variations in time and the different types of BSs considered in the model are exposed and discussed in Section 4. The model itself, based on mathematical programming, is presented in Section 5. The resolution approach, including the instance generation process and some additional tests, is discussed in Section 6 together with numerical results, whereas Section 7 concludes the paper.

2. Proposed modeling framework

From an energy savings standpoint, a radio coverage obtained using small cells served by BSs with low power is considered more convenient in terms of energy per covered area than one with macro cells of high power BSs (this may not be true for all power profiles of devices, but the trend in device technology is going in that direction [4]). In fact, when the cell radius is reduced, the energy consumption usually decreases faster than the increase of the number of BSs required to cover the area. The opposite is achieved with deployment costs, due to the fact that per-site fixed installation costs tend to prevail. Now, considering that the full coverage of the service area must be ensured at all times, a cellular system based only on small cells may not be the most energy efficient option since all cells are necessary to provide full coverage and none of them can be turned off when traffic is low. On the contrary, the availability of a potentially large number of network configurations, consisting in a set of active BSs having different capacity and energy consumption levels, is the key issue to enable efficient energy management strategies.

Therefore, claiming the key role of network flexibility and stating that energy management *must* be considered when planning the radio coverage of the cellular network, here we propose an approach that jointly optimizes the network design, based on Capex and Opex costs, as well as the power management according to different traffic levels.

The traditional models for wireless access network planning - including 2G [5], 3G [6] and Wireless LANs [7] examples - have to do with finding locations and configuration settings for network devices in order to serve the traffic demand while matching service requirements. The optimal radio planning problem, which consists in determining the best BSs locations out of a set of Candidate Sites (CSs) while insuring an appropriate signal level, results in the classical minimum cost set covering problem. Taking this basic radio planning model as starting point, we introduce the following innovative features to produce the joint design and management framework: i) The objective function not only includes BSs installation costs (Capex) but also operational ones (Opex), assuming that their variable part is largely due to the expenses related to the energy consumption; ii) Variables and constraints are redefined to include the energy management mechanism in the model and a set of traffic demands related to different time periods of the day is introduced; iii) A trade-off parameter defines the relative importance of Capex and Opex in the optimization process and can be used to compare our results with traditional Capex-only network planning or two-step planning and management approaches (see Section 6.3).

3. Related Work

Since the seminal work of Gupta and Singh [8], there has been an expansion in green networking research. Regarding wireless networks, examples of exhaustive reviews of green mobile opportunities can be found in [9, 10]. Three case studies for reducing BS power consumption are reported in [11], while other detailed investigations on energy awareness in cellular networks are described in [12, 13].

Although a large body of literature is focused on energy-efficient *devices* or *protocols*, more recent efforts are on planning or operation, but always tackling the *design* and *management* as separate problems. Considering network operation optimization, a great amount of work has appeared in the last few years. In [14], given the network topology and a fixed traffic demand, the possibility of switching off some nodes to minimize the total power consumption while respecting QoS is evaluated. However, no traffic variations in space or time are considered. Deterministic traffic variations over time are taken into account in [15] as well as in [16], where the energy saved by reducing the number of active access devices when they are not fully utilized is characterized for different cell topologies. In [17] the authors show that it is possible to switch off some UMTS Nodes in urban areas during low-traffic periods, still guaranteeing Quality of Service constraints in terms of blocking probability and electromagnetic exposure limits, while authors in [18] consider a random traffic distribution and dynamically minimize the number of active BSs to meet the traffic variations in both space and time dimensions. Moreover, [19] examines the *cell zooming* problem (i.e., the extension of a cell coverage area to guarantee service when other BSs are turned off) and assesses the possibility of modifying the cell deployment to allow higher power savings by turning off a greater number of BSs.

For what concerns network planning, [20] measures the power efficiency of a large vs. small cell deployment on a service area by the help of two performance metrics: the *energy consumption ratio*, defined as the energy per delivered information bit, and the *energy consumption gain*, which quantifies the possible savings obtaining using small cells instead of big ones. In [21] the authors divide the service area into dense and sparse zones and propose an adaptive deploying strategy where the size of the cells can be adjusted according to the varying user requests. Paper [22] evaluates the effectiveness of the joint deployment of macro cells and residential femtocells, while [23] investigates the cells layout impact on power consumption by varying the numbers of micro BSs per cell in addition to conventional macro sites. The results they provide show that the power savings are moderate in case of peak traffic scenarios and depend on the offset power of the BSs. Unlike such work, we do not limit our analysis to regular layouts and we propose an optimization approach that can be used with arbitrary topologies and propagation scenarios.

Up to now, only a few articles approached the problem of optimizing the network deployment and the energy-aware operation at the same time. In particular, the trade-off between deployment efficiency and energy efficiency is pointed out as one of the fundamental frameworks in green radio research in [24], while [25] treats it in more details, defining an analytical relation between the two terms. Another approach in the use of micro cells overlapping a pre-existing network is discussed in [26], where a two-stage greedy approach is used to upgrade the network capacity while limiting the required expenses. In the first stage, additional micro BSs are installed over a previously deployed macro cells layer to meet peak traffic demand; then, the network operation is managed with the aim of reducing power waste during off-peak periods. Differently from that article, we do not assume a pre-existing infrastructure but rather find what that infrastructure should be by jointly optimizing the planning (BS location and type) and the energy efficient operation. Moreover, not only the peak demand but all the varying demand scenarios are included in the optimization framework. A similar two-stage planning and management technique is also adopted in [27]. Here, the authors exploit a genetic algorithm to design network topologies according to three different strategies: minimization of the BSs number, of the consumed power or of both of them. A set of BSs in the total number of installed devices is then selected to be always on, even during off-peak traffic periods; the next step consists in managing the remaining access stations in order to save power when traffic is low. BSs are turned off according to two criteria: least loaded (lower number of served users) and most overlapped (highest portion of coverage area shared with neighbor BSs). In our work, contrarily, we adopt a one-step approach to point out the benefits and the topology changes that can be obtained when the network design and management are optimized in a joint fashion.

4. Preliminaries

4.1. Base Station Categories

In order to verify our claims and evaluate the proposed approach, we considered Long Term Evolution (LTE) technology test scenarios. Since we stated that network flexibility is a key factor to obtain an effective energy-efficient network management, three different BS types (called here *configurations*) are taken into account, each one allowing to be switched off in case of low traffic profile. Realistic power consumption and capacity values for BSs have been extracted from [28] and collected in Table 1, where the heading "Consumed Power" represents the mean equipment power consumption (including power amplifier, signal generator, air conditioning and microwave link). Note that we provide specific BS categories to create interesting numerical examples, but the proposed design approach is general and can be used with any mix of BS types and technologies.

4.2. Traffic Variation Behavior

Intuitively it can be said that traffic intensity varies as a natural effect of users daily habits. For example, it has been measured that mobile traffic presents its peak between noon and 4 pm and that there is a significant decrease in the late evening. Moreover, in a typical business area, the traffic pattern is almost the same from Monday to Friday but it decreases during the weekend [29]. To account for the main fluctuations, but neglecting the differences that occur between working and weekend days, we consider an approximated daily pattern based on the downlink traffic measurements

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

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

presented in [28]. According to this profile the whole day is split in time periods, each one gathering smaller intervals (hours) in which the users behavior can be assumed unchanged. We define T as the ordered set of time periods, with δ_t representing the length of period $t \in T$. The end of each time period is equal to the beginning of the new one, so that there is no time gap between adjacent periods and the summed duration of all periods is equal to the number of hours in a day. In this paper, we assume a total of eight time periods for our LTE examples. Observing Figure 1, the progress of the approximated traffic profile defines active user percentages in every time interval.

In more detail, our traffic distribution is modeled as follows. Let us define a Test Point (TP) as an aggregated traffic centroid. From now on, we will refer to typical TPs with the name of *Traffic* Test Points. For each Traffic TP we calculated a random value uniformly chosen between 20 and 40 Mb/s, together with a random number in the $[0, 1]$ interval. The first value is fixed, denoting the traffic amount that each Traffic TP provides to the network only if the second number is less or equal the normalized traffic value. Furthermore, in our modeling framework we introduce a new kind of *Coverage* Test Points, disposed on a regular square grid overlaying the whole area. Coverage TPs do not produce any traffic but, since they have to lie in at least one active cell, they are essential to ensure the total area coverage in the dimensioning phase even in the off-traffic regions.

4.3. The Propagation Model

Although, in real scenarios, the transmitted signal quality is affected by path loss, shadowing and fast fading, a common assumption in network modeling consists in omitting shadowing, while we neglect fast fading because of the characteristics of our problem (small-scale variations are fairly rapid in space).

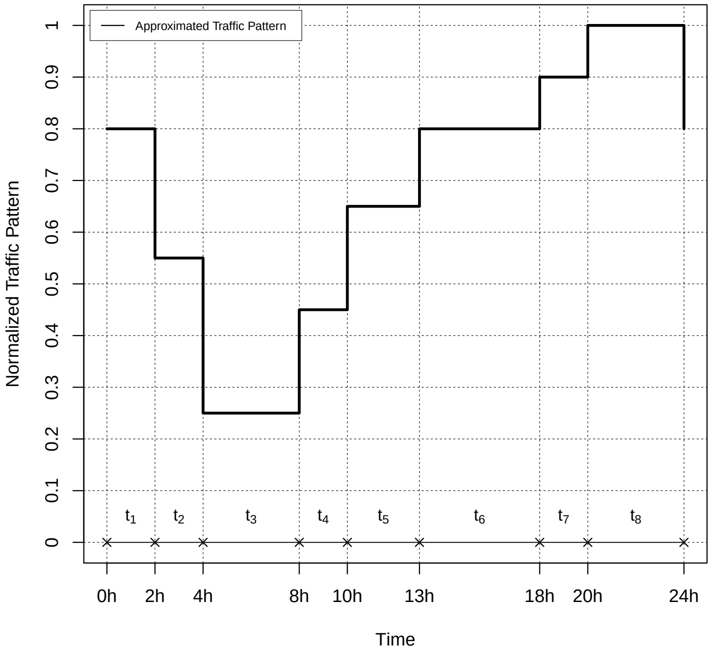

Figure 1: Approximated traffic profiles for LTE systems.

Being f ($2600\ MHz$) the operating frequency, h_b ($12\,m$, $10\,m$ or $8\,m$ according to the BS configuration) and h_r ($1.5\,m$) the correction factors for BS and user antenna height, the median path loss at a generic distance d is calculated by using the COST-231 Hata model [30]:

$$\begin{aligned}\overline{PL}(d)[dB] = 46.3 + 33.9\,Log(f) - 13.82\,Log(h_b) - a(h_r) + \\ + (44.9 - 6.55\,Log(h_b))\,Log(d) + c_m.\end{aligned} \tag{1}$$

The parameter c_m is equal to zero for suburban areas, while the function $a(h_r)$ is defined as:

$$a(h_r) = (1.1\,Log(f) - 0.7)h_r - (1.56\,Log(f) - 0.8). \tag{2}$$

Finally, cable losses are 2 dB while antenna gains are assumed to be 15 dB for configurations $C1$, $C2$ and 12 dB for $C3$.

5. The Joint Design and Management Framework

Let us define the model *parameters:*

I_c : Set of *Coverage* TPs, which do not generate any traffic but help provide a basic, fixed network coverage even in case of very low traffic profile.
I_t : Set of *Traffic* TPs, which allow the network to "follow" traffic changes in the different time periods by generating variable traffic.
S : Set of available CSs for the BSs.
K_j : Set of possible configurations for a BS located in site $j \in S$.
T : Set of time intervals.
δ_t : Duration of time period $t \in T$.
p_{it} : Traffic provided by the Traffic TP $i \in I_t$ in period $t \in T$.
c_{jk} : Capacity of the BS located in site $j \in S$ with configuration $k \in K_j$.
γ_{jk} : Installation cost for a BS located in site $j \in S$ with configuration $k \in K_j$. This is composed of the cost due to the characteristics of the chosen site (for example, open spaces or buildings) and the cost specific for the selected configuration.
ϵ_{jk} : Power consumption for a BS located in site $j \in S$ with configuration $k \in K_j$.
r_{ij} : Distance between the Traffic TP $i \in I_t$ and the BS located in site $j \in S$.
φ : Cost of the energy consumption over the entire network life. This parameter is defined as $E \cdot 365 \cdot n \cdot 0.001$, where E represents the energy cost (€) per kWh, n stays for the years over which the Opex

costs are computed (365 days in a year), and the factor 0.001 is used to convert from Wh to kWh. In this paper, we will consider $E = 0.35$ €/kWh and $n = 8$, which lead to $\varphi = 1$.

β, ϑ : Weight parameters that will be used for trading-off the objective function.

To conclude the model parameters, we need to introduce a binary one that summarizes the coverage information for each combination of TP and CS:

$$a_{ijk} = \begin{cases} 1 & \text{if TP } i \in I_c \cup I_t \text{ is in the coverage area of a BS} \\ & \text{ installed in } j \in S \text{ with configuration } k \in K_j, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Let us now define the z, y and x *decision variables* that represent, respectively, the choice of BS location and configuration type, the BS status (active or idle) and the TP assignments:

$$z_{jk} = \begin{cases} 1 & \text{if a BS is installed in site } j \in S \text{ with configuration} \\ & k \in K_j, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

$$y_{jkt} = \begin{cases} 1 & \text{if a BS installed in site } j \in S \text{ with configuration} \\ & k \in K_j \text{ in period } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

$$x_{ijt} = \begin{cases} 1 & \text{if TP } i \in I_t \text{ is assigned to a BS in site } j \in S \text{ in} \\ & \text{period } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

Then, the Joint Cellular Planning and Energy Management Problem (JCPEM) can be defined as follows:

$$\min \quad \sum_{j\in S}\sum_{k\in K_j} z_{jk}\gamma_{jk} + \beta\,\varphi \sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T}\epsilon_{jk}\delta_t y_{jkt} + \vartheta \sum_{i\in I_t}\sum_{j\in S}\sum_{t\in T} x_{ijt}\delta_t r_{ij} \tag{7}$$

$$\text{s.t.} \quad \sum_{j\in S}\sum_{k\in K_j} a_{ijk} y_{jkt} \geq 1 \qquad \forall i \in I_c \cup I_t, t \in T \tag{8}$$

$$x_{ijt} \leq \sum_{k\in K_j} a_{ijk} y_{jkt} \qquad \forall i \in I_t, j \in S, t \in T \tag{9}$$

$$\sum_{i\in I_t} x_{ijt} p_{it} \leq \sum_{k\in K_j} c_{jk} y_{jkt} \qquad \forall j \in S, t \in T \tag{10}$$

$$\sum_{j\in S} x_{ijt} = 1 \qquad \forall i \in I_t, t \in T \tag{11}$$

$$y_{jkt} \leq z_{jk} \qquad \forall j \in S, k \in K_j, t \in T \tag{12}$$

$$\sum_{k\in K_j} z_{jk} \leq 1 \qquad \forall j \in S \tag{13}$$

$$z_{jk} \in \{0,1\} \qquad \forall j \in S, k \in K_j \tag{14}$$

$$x_{ijt} \in \{0,1\} \qquad \forall i \in I_t, j \in S, t \in T \tag{15}$$

$$y_{jkt} \in \{0,1\} \qquad \forall j \in S, k \in K_j, t \in T \tag{16}$$

The objective function (7) is composed of three parts: the Capex term, which accounts for the equipment installation costs, the Opex one, that considers the energy expenses over the entire network lifetime, and a final term to guarantee a better connection quality between users and antennas. In the case of the results presented in this paper, however, we verified that the third component, introduced to push the assignment of each TP to the nearest available BS, does not have any influence on the choice of the serving BS. For this reason, we set the trade-off parameter ϑ to 0. On the other hand, by playing with the trade-off parameter β, the relative weight of the Capex and Opex components can be modified. Setting β to 0, Opex costs are excluded from the objective function and only the installation investments are minimized: the resulting network will deploy a minimum cost topology. When β is equal to 1, the energy management mechanism is enabled and forces the model to reduce not only capital but also operational costs by introducing the Opex term in the objective function. Finally, higher values of β show the network topology changes and the greater energy savings that can be obtained when growing importance is given to the Opex component.

Concerning constraints, we introduce two sets of *coverage constraints.* (8) provide a minimal, constant coverage by ensuring that all the TPs are within the service area of at least one active BS, while (9) assign Traffic TPs only to a BS they are covered by. *Capacity constraints* (10) guarantee that each active BS can satisfy the traffic demand of the assigned Traffic TPs and *assignment constraints* (11) impose that every Traffic TP is assigned to only one BS. (12) are *linking constraints* between variables y and z, while *configuration constraints* (13) impose that at most one BS configuration is installed in a CS. Finally, (14), (15) and (16) impose the binary values for the decision variables.

JCPEM, which is a linear binary problem, is NP-hard.

6. Resolution Approach and Numerical Examples

6.1. Instance Generation

The proposed mathematical model was implemented on AMPL and solved with CPLEX branch and bound solver [31], which produced optimality gaps below 5% for the experimented instances. The resolution time ranged from a few seconds to approximately half an hour, depending on the value of β and on the scenario dimension. To test the effectiveness of the proposed model, we designed and implemented in C++ an Instance Generator which creates realistic cellular network scenarios where the number of CSs and TPs is similar to the one that can be found in real networks. The features of our test scenarios are described in Table 2: the first entry represents the area size (expressed in square kilometers), the second one is the number of CSs randomly located in the considered region and next are the number of Coverage TPs (TPCs), placed on a regular grid which covers the service area. The last entry displays the number of Traffic TPs (TPTs), evenly randomly positioned in the whole area (Scenario 1 and 2) or placed with a higher probability in a smaller region that can represent, for example, a built-up area in the countryside or the center of a big city (Scenario 3-3a-3b-3c). For every scenario, different values of the weight parameter β were tested: by doing so, we strove to highlight the benefits achieved by jointly minimizing costs and power expenditures in the design and management phases, instead of limiting the optimization at the network planning stage.

6.2. Additional Tests

In order to evaluate the value of the proposed approach, we compared our results with those obtained by separately optimizing, first, the network

Table 2: Parameters used for generating the test scenarios.

	Area (km^2)	CSs	TPCs	TPTs	Allowed Config.
Scenario 1	2×2	40	121	30	All
Scenario 2	5×5	60	676	60	All
Scenario 3	4×4	120	441	40	All
Scenario 3a	4×4	120	441	40	C1, C2
Scenario 3b	4×4	120	441	40	C1, C3
Scenario 3c	4×4	120	441	40	C2, C3

design, and then, the network management. The common *two-step* approach has been reproduced by adapting our model in the following steps:

1. Run the JCPEM with $\beta = 0$ to choose the minimum cost topology without considering the energy management;
2. Fix variables z_{jk} according to the results of the previous step: this way, locations and characteristics of installed BSs will be defined;
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.

Moreover, since data traffic in cellular networks is typically *bursty* (that is to say, users are likely to provide traffic only in certain time intervals, while they are silent for the rest of the time), we observed that greater energy savings could be reached if the network service was limited only to active Traffic TPs. So, as JCPEM, this problem variation aims at providing a full-coverage network deployment, but now the objective is that of guaranteeing service only to the users that are requiring traffic in any time period, allowing to turn off those BSs which have only inactive users in their coverage region. To model the *partial coverage* approach, we need to introduce a new set of binary parameters m_{it} that are equal to 1 if Traffic TP i is active in time period t. Then, constraints (8) in the original model are replaced by:

$$\sum_{j \in S} \sum_{k \in K_j} a_{ijk} z_{jk} \geq 1 \qquad \forall i \in I_c \cup I_t, \tag{17}$$

meaning that every Coverage or Traffic TP has to be covered by an *installed* BS, regardless of its on or off state, while constraints (11) become:

$$\sum_{j \in S} x_{ijt} = m_{it} \qquad \forall i \in I_t, t \in T, \tag{18}$$

since network service is provided only to active clients. The partial coverage problem can be written as:

$$\begin{aligned} \min \qquad & (7) && (19)\\ \text{s.t.} \qquad & (9), (10), (12) \text{ to } (18). && (20) \end{aligned}$$

Note that the partial coverage case cannot be implemented in current mobile network technologies where continuous and full coverage must be ensured. However, new access architectures have been recently proposed and are currently being considered by standardization bodies where the control and data plane are separated at the the radio interface [32]. Such a separation allows data BSs to be turned off when no active user is under their coverage area, since a continuous access availability is guaranteed by the always-on signaling BSs.

6.3. Numerical Results

In order to appreciate the results of the joint approach and the differences with the two proposed variations, in what follows we concentrate mainly on pictures representing some important results from Scenario 2. Traffic TPs are symbolized by black dots, while Coverage TPs are arranged on a regular grid every 200 m. Only selected CSs are depicted: switched-on BSs are represented as black triangles, while switched-off BSs as white ones.

Let us focus on Figure 2, which displays the network obtained for Scenario 2 when the Capex and Opex are optimized in two separate steps. Since in the first step only capital costs are minimized, the network planning recalls the capacitated facility location problem and the installed BSs represent the minimum cost network topology. We note that as much as 5 type $C1$ BSs are deployed and, together with 11 additional type $C2$ BSs, they can cover the whole area. However, due to the fact that the traffic required by Traffic TPs is high compared to BS capacity, 7 type $C3$ antennas are also required to serve the users demand. Despite the apparently effective operation of the energy aware mechanism (see Figure 3, displaying the turned-on BS during off-peak traffic period), the Opex expenses are just slightly lowered, if compared to the non-managed network operation; in fact, only the smallest

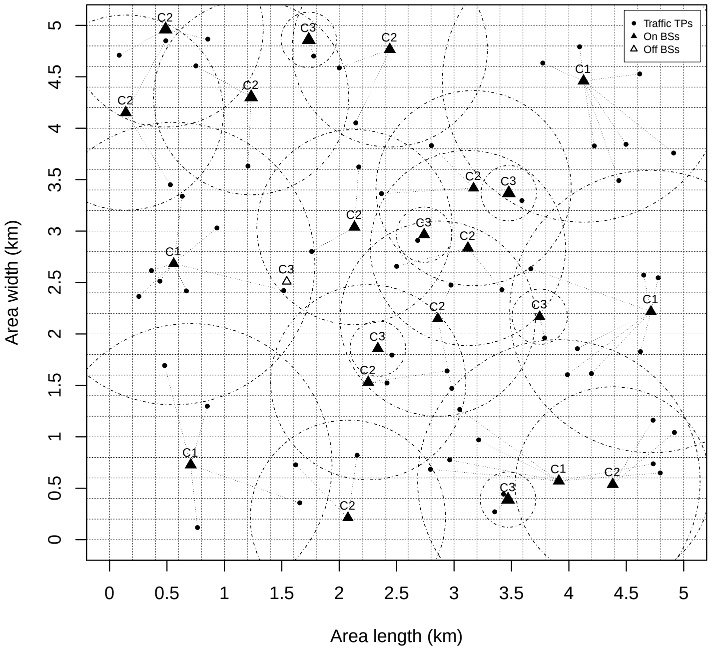

Figure 2: Scenario 2, $\beta = 0$ (2-step, total coverage), t_8: 22 BSs on out of 23.

and least power consuming BS can be turned off, while the biggest BS have to guarantee the area coverage at all times. Figures 4 and 5 show how the joint design and management model modifies the network topology and operation chosen for Scenario 2 by the separate approach. The first picture represents the network behavior in the peak-traffic time period t_8 when β is set to 1. Differently from the two-step case described above, 30 BSs instead of 23 have been installed at the cost of a 4% Capex increase, corresponding to 10000 €. Due to a lower installation cost per covered square kilometer (4405 €, compared to 6315 € for $C1$ and 5494 € for $C3$), most of them are type $C2$ (21), while 2 type $C1$ and 7 type $C3$ cells are still necessary to guarantee the total area coverage and support intermediate BSs serving TPs traffic.

The network management mechanism achieves more striking energy and cost savings if we allow a BS to be turned off when it has no active Traffic TPs in its coverage area. In this case, no network service is supplied to silent users; however, due to the full coverage nature of the deployed network, as

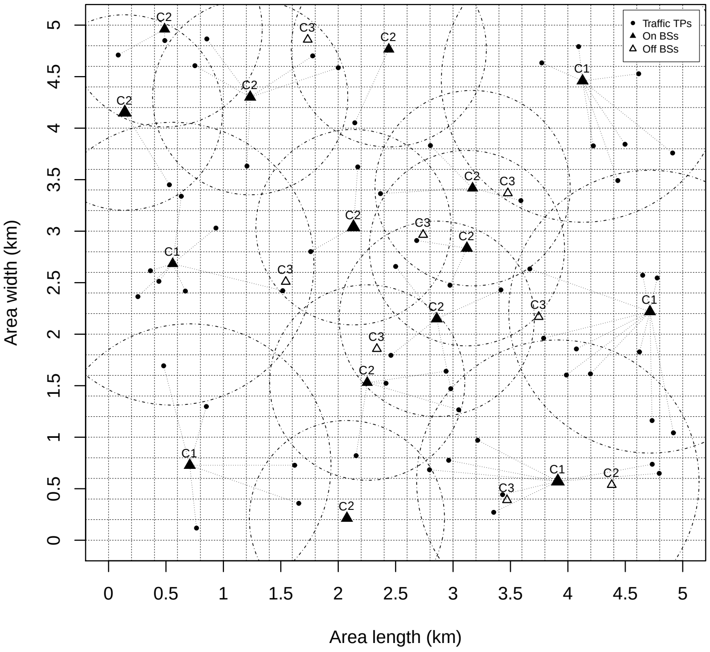

Figure 3: Scenario 2, $\beta = 0$ (2-step, total coverage), t_3: 15 BSs on out of 23.

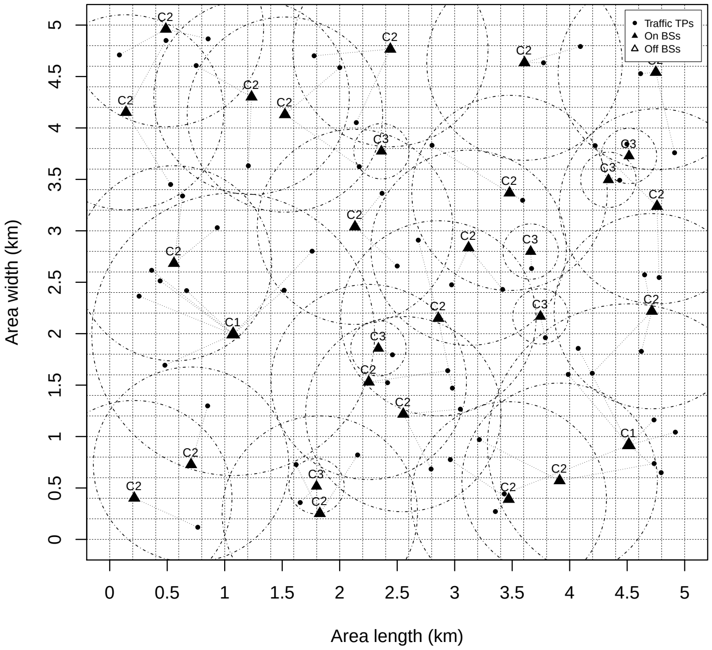

Figure 4: Scenario 2, $\beta = 1$ (joint, total coverage), t_8: 30 BSs on out of 30.

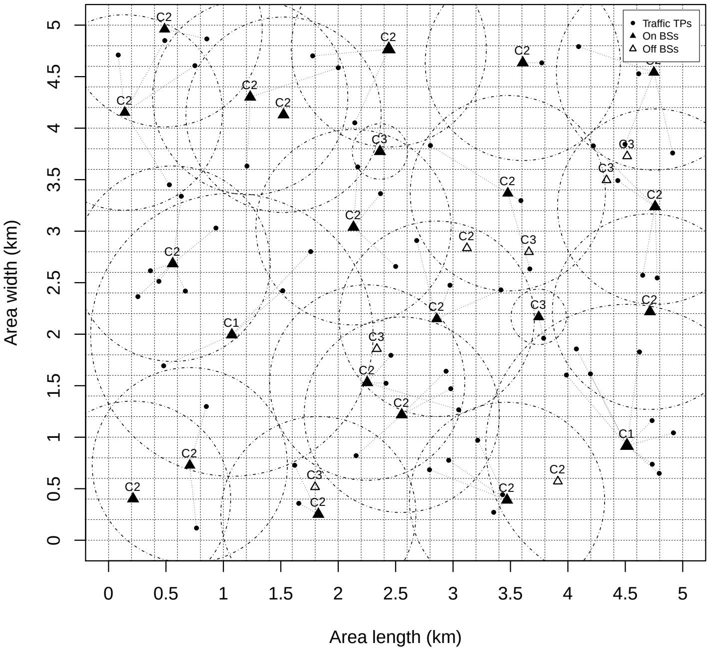

Figure 5: Scenario 2, $\beta = 1$ (joint, total coverage), t_3: 23 BSs on out of 30.

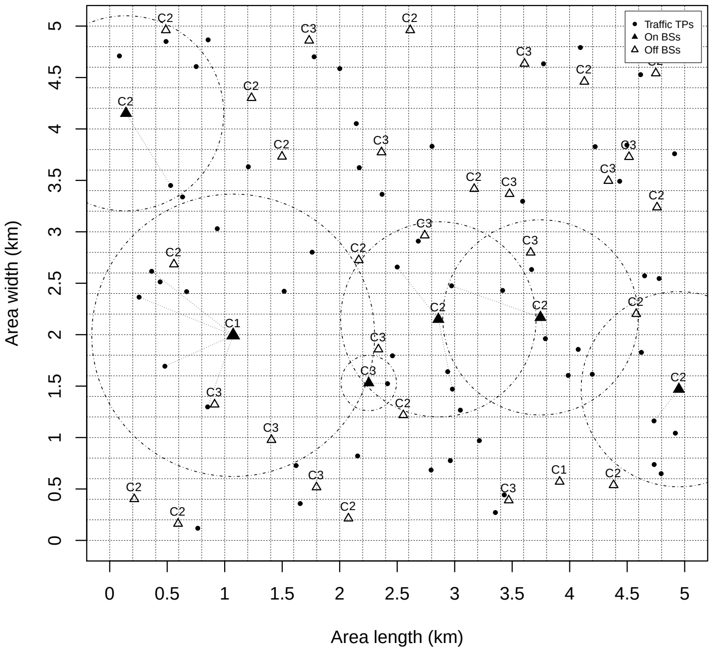

Figure 6: Scenario 2, $\beta = 1$ (joint, partial coverage), t_3: 6 BSs on out of 36.

Table 3: Results obtained by applying the joint model with total coverage to Scenario 1.

	$\beta = 0$	2-step	$\beta = 1$	$\beta = 5$	$\beta = 10$
Time	44 s	1 s (oper)	25 m 11 s	11 m 49 s	11m 1 s
Capex (k€)	56	56	62 *(+11%)*	64 *(+14%)*	66 *(+18%)*
Opex (k€, 8 year)	42	39 *(-7%)*	19 *(-55%)*	18 *(-57%)*	17 *(-60%)*
Installed BSs	18	18	17	19	21
Conf. Types	C1 - 1 C2 - 1 C3 - 16	C1 - 1 C2 - 1 C3 - 16	C1 - 0 C2 - 5 C3 - 12	C1 - 0 C2 - 5 C3 - 14	C1 - 0 C2 - 5 C3 - 16
On BSs	T1 - 18 T2 - 18 T3 - 18 T4 - 18 T5 - 18 T6 - 18 T7 - 18 T8 - 18	T1 - 16 T2 - 9 T3 - 4 T4 - 8 T5 - 13 T6 - 14 T7 - 16 T8 - 17	T1 - 17 T2 - 10 T3 - 4 T4 - 10 T5 - 15 T6 - 15 T7 - 15 T8 - 17	T1 - 17 T2 - 10 T3 - 4 T4 - 10 T5 - 16 T6 - 16 T7 - 16 T8 - 17	T1 - 17 T2 - 10 T3 - 4 T4 - 11 T5 - 15 T6 - 15 T7 - 17 T8 - 18

soon as a TP switches from the idle to the active state, an additional BS can be turned on to route the new provided traffic. The outcome of the partial coverage approach, as called in Section 6.2, is displayed in Figure 6 for $\beta = 1$. Time period t_3 has been represented to point out the great difference with the previous examples: here we observe that only 6 BSs can serve the traffic requested by active users, but as much as 36 BSs are installed to ensure the area full coverage. Note that, to further increase the operational savings, the deployed network counts 6 more BSs than the topology obtained by using the joint approach with the same value of $\beta = 1$ (Figures 4 and 5). With reference to the joint optimization cases described above, where each TP had to lie in the coverage region of an active BS, 31% of energy savings ($\beta = 1$) are expected if the partial coverage approach is adopted, corresponding to almost 5250 € spared every year; moreover, the percentage raises to 61% when compared to the two-step total coverage approach depicted in Figure 2, which is equivalent to 13250 € yearly savings.

Tables 4 and 6 summarize the results obtained solving Scenario 2 with, respectively, the total and partial coverage models, using different values of the trade-off parameter β. Also, Tables 3 and 5 display the results for scenario 1 in the same cases. The following entries are reported:

1. The resolution time required by CPLEX to optimize the test instances;

Table 4: Results obtained by applying the joint model with total coverage to Scenario 2.

	$\beta = 0$	2-step	$\beta = 1$	$\beta = 5$	$\beta = 10$
Time	25 s	1 s (oper)	1 m 51 s	1 m 7 s	19 s
Capex (k€)	267	267	277 *(+4%)*	298 *(+12%)*	299 *(+12%)*
Opex (k€, 8 year)	203	198 *(-3%)*	134 *(-34%)*	115 *(-43%)*	115 *(-43%)*
Installed BSs	23	23	30	33	34
Conf. Types	C1 - 5 C2 - 11 C3 - 7	C1 - 5 C2 - 11 C3 - 7	C1 - 2 C2 - 21 C3 - 7	C1 - 2 C2 - 23 C3 - 8	C1 - 2 C2 - 23 C3 - 9
On BSs	T1 - 23 T2 - 23 T3 - 23 T4 - 23 T5 - 23 T6 - 23 T7 - 23 T8 - 23	T1 - 18 T2 - 14 T3 - 15 T4 - 14 T5 - 15 T6 - 18 T7 - 21 T8 - 22	T1 - 26 T2 - 22 T3 - 23 T4 - 22 T5 - 23 T6 - 27 T7 - 28 T8 - 30	T1 - 29 T2 - 23 T3 - 23 T4 - 23 T5 - 24 T6 - 29 T7 - 29 T8 - 30	T1 - 29 T2 - 22 T3 - 22 T4 - 22 T5 - 26 T6 - 30 T7 - 30 T8 - 31

2. Capital Expenditures (Capex), expressed in Euro and corresponding to the value of the first component of the objective function;
3. Operational expenses for the whole network, calculated over a 8 year period by considering the Italian energy cost for business users of 0.35 € per kiloWatt hour;
4. Number and type of BSs installed in the area;
5. Number of BSs powered on during every time period.

Percentages in parenthesis express the Capex and energy consumption increase/descrease with respect to the case when $\beta = 0$ and only capital costs are minimized. Moreover, Tables 5 and 6 include percentage variations in Capex and Opex with respect to the corresponding examples in Table 3 and Table 4.

As already pointed out, increasing the value of β means increasing the installation costs as well as the number of BSs, while decreasing the total energy consumed. The same behavior can be observed for all test scenarios: taking as an example the results in Table 3, obtained for Scenario 1 by applying the original joint model, the Capex growth turns out to be 11% with $\beta = 1$, 14% with $\beta = 5$ and 18% with $\beta = 10$ with respect to the

Table 5: Results obtained by applying the joint model with partial coverage to Scenario 1.

	$\beta = 0$	2-step	$\beta = 1$	$\beta = 5$	$\beta = 10$
Time	27 s	1 s (oper)	28 m 28 s	16 m 49 s	22 m 12 s
Capex (k€)	56	56	62 *(+11%)*	66 *(+18%)*	66 *(+18%)*
Vs. Total Coverage	+0%	+0%	+0%	+3%	+0%
Opex (k€/8 year)	42	33 *(-21%)*	16 *(-62%)*	14 *(-67%)*	13 *(-69%)*
Vs. Total Coverage	-0%	-15%	-16%	-22%	-24%
Installed BSs	18	18	17	21	21
Conf. Types	C1 - 1 C2 - 1 C3 - 16	C1 - 1 C2 - 1 C3 - 16	C1 - 0 C2 - 5 C3 - 12	C1 - 0 C2 - 5 C3 - 16	C1 - 0 C2 - 5 C3 - 16
On BSs	T1 - 18 T2 - 18 T3 - 18 T4 - 18 T5 - 18 T6 - 18 T7 - 18 T8 - 18	T1 - 15 T2 - 7 T3 - 1 T4 - 7 T5 - 12 T6 - 13 T7 - 14 T8 - 16	T1 - 17 T2 - 11 T3 - 1 T4 - 11 T5 - 15 T6 - 14 T7 - 15 T8 - 17	T1 - 18 T2 - 12 T3 - 1 T4 - 11 T5 - 16 T6 - 15 T7 - 17 T8 - 19	T1 - 18 T2 - 12 T3 - 1 T4 - 11 T5 - 16 T6 - 15 T7 - 16 T8 - 19

Table 6: Results obtained by applying the joint model with partial coverage to Scenario 2.

	$\beta = 0$	2-step	$\beta = 1$	$\beta = 5$	$\beta = 10$
Time	16 s	1 s (oper)	2 m 20 s	2 m 13 s	2 m 47 s
Capex (k€)	267	267	274 *(+3%)*	340 *(+27%)*	362 *(+36%)*
Vs. Total Coverage	+0%	+0%	+1%	+14%	+21%
Opex (k€/8 year)	202	175 *(-13%)*	92 *(-54%)*	75 *(-63%)*	73 *(-64%)*
Vs. Total Coverage	-0.5%	-12%	-31%	-35%	-37%
Installed BSs	23	23	36	37	39
Conf. Types	C1 - 5 C2 - 11 C3 - 7	C1 - 5 C2 - 11 C3 - 7	C1 - 2 C2 - 20 C3 - 14	C1 - 3 C2 - 24 C3 - 10	C1 - 4 C2 - 23 C3 - 12
On BSs	T1 - 23 T2 - 22 T3 - 21 T4 - 22 T5 - 22 T6 - 23 T7 - 23 T8 - 23	T1 - 17 T2 - 12 T3 - 6 T4 - 9 T5 - 13 T6 - 15 T7 - 21 T8 - 22	T1 - 30 T2 - 17 T3 - 6 T4 - 15 T5 - 21 T6 - 23 T7 - 28 T8 - 32	T1 - 30 T2 - 18 T3 - 7 T4 - 14 T5 - 22 T6 - 29 T7 - 25 T8 - 29	T1 - 31 T2 - 19 T3 - 7 T4 - 14 T5 - 22 T6 - 29 T7 - 26 T8 - 30

Table 7: Significative results obtained applying joint model with total and partial coverage ($\beta = 1$) to Scenario 4 and its variations.

	Scen. 3	Scen. 3a	Scen. 3b	Scen. 3c
Total Coverage :				
Capex (k€)	136	240 *(+76%)*	190 *(+40%)*	137 *(+0.7%)*
Opex (k€/8 years)	46	71 *(+54%)*	197 *(+328%)*	46 *(+0%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - -
	C2 - 12	C2 - 24	C2 - -	C2 - 12
	C3 - 16	C3 - -	C3 - 10	C3 - 17
On BSs in t_3	C1 - 0	C1 - 0	C1 - 6	C1 - -
	C2 - 12	C2 - 14	C2 - -	C2 - 12
	C3 - 5	C3 - -	C3 - 2	C3 - 5
On BSs in t_8	C1 - 0	C1 - 0	C1 - 6	C1 - 0
	C2 - 12	C2 - 24	C2 - -	C2 - 12
	C3 - 15	C3 - -	C3 - 9	C3 - 17
Partial Coverage:				
Capex (k€)	144	240 *(+67%)*	208 *(+44%)*	141 *(-2%)*
Opex (k€/8 years)	16	50 *(+213%)*	56 *(+250%)*	15 *(-6%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - -
	C2 - 12	C2 - 24	C2 - -	C2 - 12
	C3 - 24	C3 - -	C3 - 28	C3 - 21
On BSs in t_3	C1 - 0	C1 - 0	C1 - 0	C1 - -
	C2 - 2	C2 - 6	C2 - -	C2 - 1
	C3 - 6	C3 - -	C3 - 7	C3 - 6
On BSs in t_8	C1 - 0	C1 - 0	C1 - 2	C1 - -
	C2 - 4	C2 - 19	C2 - -	C2 - 3
	C3 - 22	C3 - -	C3 - 22	C3 - 20

two-step approach. Power demand, on the other hand, decreases 55% when $\beta = 1$, 57% when $\beta = 5$ and 60% when $\beta = 10$. With easy calculations, we found that when the trade-off parameter is set to 5, the extra capital investment, corresponding to 8000 €, can be retrieved in approximately 3 years from the savings in network operation, amounting to 2625 € per year. If we now consider the partial coverage variation and the same value of β, an additional 22% (corresponding to 4000 €, or 25000 € compared to the two-step results) can be saved in operational expenses at the cost of only 3% further increase in Capex. Looking at tables 3 to 6, it is also worth underlining that, when β assumes values grater than 1, some deployed BSs are switched off not only during low traffic periods as t_3, but even when in maximum traffic, giving more importance to operation effectiveness with respect to capital savings.

Finally, we propose in Table 7 a comparison between the solutions achieved by applying the total and partial coverage joint models ($\beta = 1$) on Scenario 3 and its variations. As shown in Table 2, we created three alternative forms of Scenario 3, distinguished only by the fact that two out of three BS configurations can be installed: Scenario 3a allows configurations $C1$ and $C2$, Scenario 3b deploys only $C1$ and $C3$ while Scenario 3c admits configurations $C2$ and $C3$. By doing so, we try to demonstrate that flexibility is an essential network characteristic when the purpose is to guarantee an effective network operation, that is to say, maximizing the energy savings. As we can see from the table, Scenarios 3a and 3b behave poorly if compared to Scenario 3 and 3c: forbidding the installation of one of the two smaller configuration $C2$ and $C3$, the joint model is forced to deploy a higher number of bigger cells which, besides being expensive in terms of Capex, consume a large amount of energy even when the total coverage is not required. So, for example, during time period t_8, 2 $C1$ BSs (in addition to 22 $C3$ BSs) are switched on in Scenario 3b when only active TPs have to be covered. On the other hand, observing Scenario 3, 4 $C2$ and 22 $C3$ cells are enough for serving the traffic provided by TPs in the busiest period, decreasing power consumption at almost one-fourth compared to the previous case. Similar results (but setting $\beta = 10$) are represented in Figures 9 and 10, while Figures 7 and 8 report the network topology obtained when the total area coverage is needed at all time.

7. Conclusion

Managing the network operation to follow traffic variations is certainly one of the most powerful instruments in mobile operator hands to reduce energy consumption, and so, operational costs. By proposing an optimization framework that selects the BSs to be installed and jointly switches them on and off according to the changing traffic load, in this paper we strove to demonstrate that for the power management to be truly effective networks have to be *designed* taking into account operational management.

The goal of our approach is not only to minimize both installation and operational costs, but also to find the best trade-off between keeping low initial investments and reducing energy consumption. Varying the trade-off parameter β between Capex and Opex, we got network topologies with different characteristics. Networks with a low installation cost are not very efficient from an energy consumption standpoint since those tend to use mostly big cells. On the other hand, the most energy efficient networks include not only small cells with low energy consumption, but also some bigger cells to

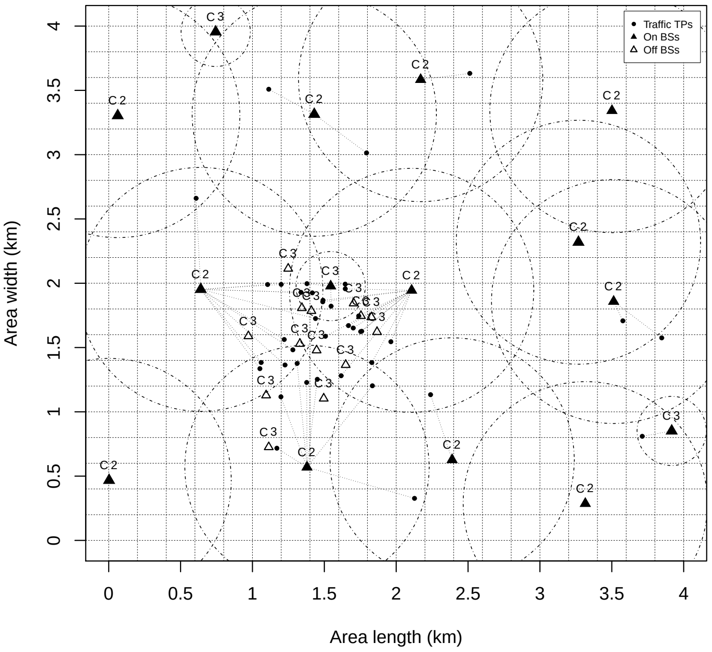

Figure 7: Scenario 4, $\beta = 10$ (joint, total coverage), t_3.

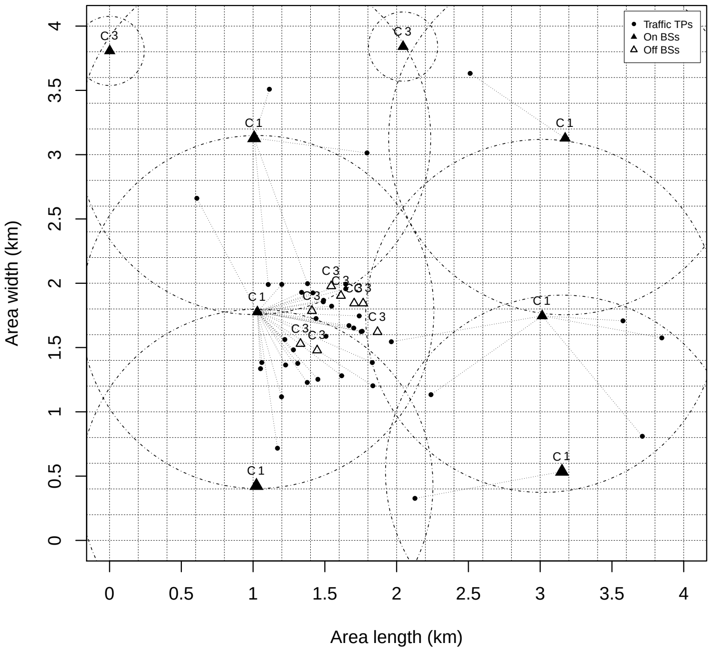

Figure 8: Scenario 4b, $\beta = 10$ (joint, total coverage), t_3.

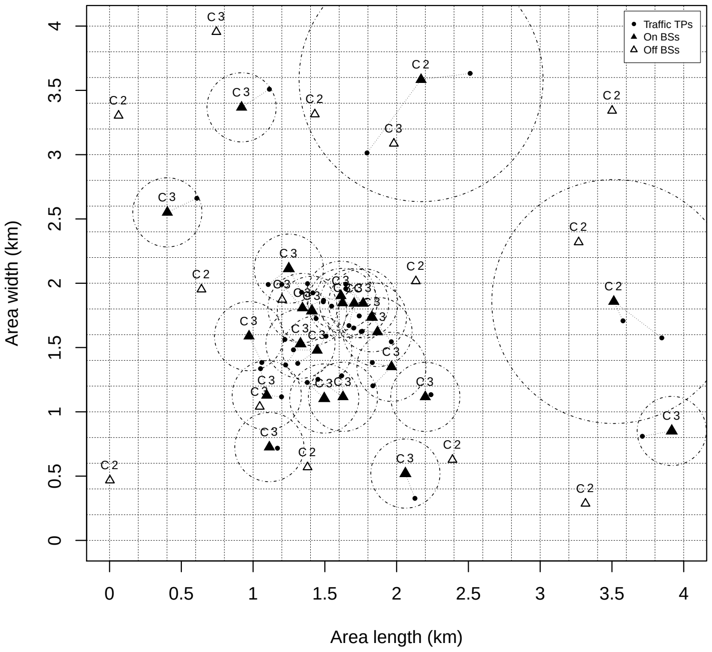

Figure 9: Scenario 4, $\beta = 10$ (joint, partial coverage), t_8.

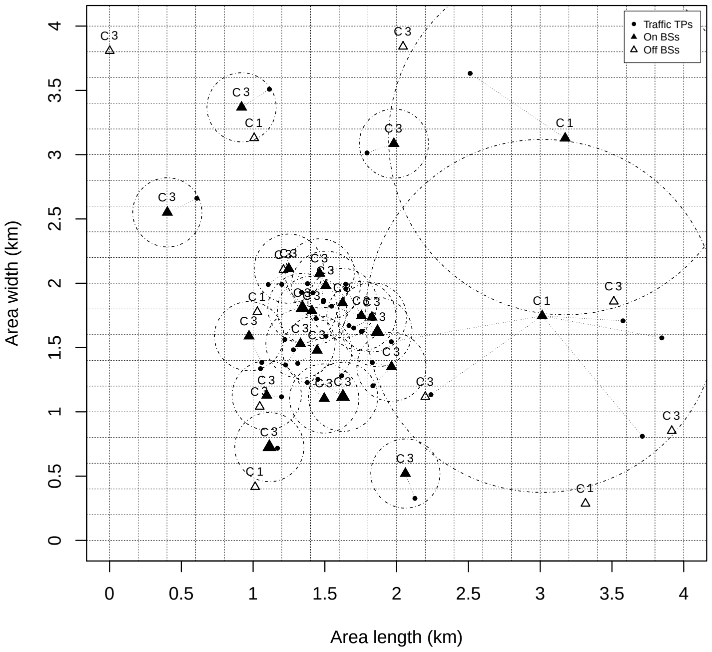

Figure 10: Scenario 4b, $\beta = 10$ (joint, partial coverage), t_8.

provide the energy management mechanism with enough flexibility to adapt the network capacity in different time periods.

Future work will consider heuristic methods for very large scale network instances and the development of real-time on-line operation models incorporating user mobility.

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