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Energy-aware planning and management of wireless mesh networks

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Abstract: In this paper we introduce a joint planning and energy management framework for Wireless Mesh Networks. In order to show that power management should be integrated at the planning steps to produce an effective energy-efficient network, we present a mathematical model considering a trade-off between capital and energy-related operational expenses. Results demonstrating the impact of different coverage strategies on the energy efficiency are also showed.

1 Introduction

The rising demand for pervasive information access is causing the ICT industry to have a significant impact on the world energy consumption [1], with the telecommunications sector representing almost 50% of the overall power expenses [2]. *Green networking* has therefore recently emerged as a new way of building and managing communication networks to improve their energy efficiency and reduce environmental impact while decreasing *Opex* (Operational Expenditures) related power expenses.

Due mostly to the fact that Wireless Access Networks (WANs) are dimensioned to meet the QoS needs in full traffic load conditions, resulting to be over-provisioned during off-peak periods, the access is the most energy hungry network segment, being responsible for 80% of the total power requirement [2, 3]. Different approaches have been proposed to reduce the energy waste of access elements (see [4] and [5] for an overview on wireless and wireline networks). In Wireless Local Area Networks (WLANs) we can mention [6], proposing a Resource on-Demand (RoD) approach which aims at powering off some access points during low traffic periods, or [7] and [8], the first exploring two different on-Demand strategies and the latter exploiting RoD to investigate the trading relationship among different types of wireless resources. Concerning cellular access, [9] and [10] consider the traffic variations to switch off underutilized nodes while [11] proposes to upgrade the network capacity in an energy-efficient way by installing and operating an additional layer of micro cells.

Despite the great interest in power saving topics, the literature has so far disregarded a fundamental issue: in order to have an effective energy-aware operation, which is tightly related to planning decisions, the power management *must* be taken into account at the design stages to be able to optimize energy related Opex later on. So far as we know, such an approach has been adopted only in our own previous work on cellular networks [12], where we developed a joint design and management model that aims at limiting both energy consumption and installation expenditures.

This paper focuses on Wireless Mesh Networks (WMNs), providing wireless connectivity by mean of cheap and low transmission power devices which can self-organize and self-configure for creating an ad hoc network [13]. However, since infrastructure devices in WMNs remain active during the whole day, the energy consumption is constantly high, while it would be possible to save a large amount of power by switching off unneeded nodes during low traffic periods. To this end in [14], starting from a deployed network, an optimization model is proposed for dynamically selecting a subset of routers and access points to be turned on following the traffic variations; even so, energy management is still considered as an exclusively operational feature. Differently, here we aim at demonstrating that, given the highly adaptive features of the mesh architecture, a joint planning and management approach can provide further energy efficiency improvements. To validate our claim, we will compare the results given by our model with those obtained when design and energy-aware operation are performed in separate stages. Furthermore, a comparison of the savings achieved for mesh and cellular networks exploiting the same modeling philosophy will be presented.

The reminder of the paper is organized as follows. Section 2 provides a description of the wireless mesh systems and the traffic pattern considered for our test experiences, then introduces the joint optimization framework. The resolution approach is described in Section 3, where we also explain the model variations used for evaluating the effectiveness of our optimization method. Numerical results are fully commented in Section 4, while Section 5 concludes the paper.

2 Joint WMNs design and management

2.1 Preliminaries

In WMNs there are two types of Base Stations (BSs): Mesh Routers (MRs) and Mesh Access Points (MAPs). The first provide network access for the Mesh Clients (MCs) and forward their messages to other routers through point to point wireless links, while the latter act as routers as well as Internet gateways. As in [14], we consider all devices having multiple network interfaces to reduce interference. The standard chosen for the BSs is Wi-Fi 802.11n with a nominal bidirectional link capacity of $450\,Mbps$ and a coverage ray of $450\,m$. MCs are connected through the nearest active router to the Internet by multi-hop communications, employing the access technology Wi-Fi 802.11g with 54 $Mbps$ shared among all users of a single BS. Also, a MC can be served by a BS only if it is within a 250 m coverage range. For our tests we assume a backbone link capacity unvarying with the distance; however, for justifying our assumption, we also solved the model proposed in Section 2.2 by setting different values of link capacity, depending on the BSs mutual distance. The obtained results confirmed our hypothesis that a fixed capacity does not remarkably affect the Capex and Opex expenses, as well as the network devices deployment.

Concerning traffic demand fluctuations, measurements for WANs can be found in several studies [15, 16]. Starting from an approximated traffic profile based on these evaluations, in [14] the whole day is divided in time periods in which users behavior is held as unchanged. Let $T = [t_1, t_2 ... t_8]$ be the ordered set of time periods. The following set of triplets gives the specific interval, the span of time it represents and the probability that a MC provides traffic to the network (or, in other words, the percentage of active users): $(t_1, [0h, 3h], 0.35)$, $(t_2, [3h, 6h], 0.1)$, $(t_3, [6h, 9h], 0.45)$, $(t_4, [9h, 12h], 1)$, $(t_5, [12h, 15h], 0.7)$, $(t_6, [15h, 18h], 0.85)$, $(t_7, [18h, 21h], 0.6)$, $(t_8, [21h, 24h], 0.5)$.

2.2 Notational framework

Parameters

- M : Set of MCs requesting traffic;
- S : Set of CSs (Candidate Sites, i.e. possible locations for installing the BSs);
- T : Set of time periods;
- $J_h^{(i)}$: Subset of BSs covering MC i, ordered from the closest to the furthest;
- B_i : Number of BSs covering MC i;
- d_{it} : Traffic provided by MC i in period t, randomly generated between 1 and 10 $Mbps$;
- c_j : Access capacity of the BS in site j (40 $Mbps$);
- u_{jl} : Capacity of the wireless link between BSs in sites j and l (300 $Mbps$);
- m : Capacity of the MAP Internet access (10 $Gbps$);
- γ_j : Installation cost for a MR in site j (200 €);
- p_j : Installation cost for a MAP in site j, including the cost for connecting it to the wired backbone (400 €);
- ϵ_j : Power consumption for a MR in site j (15 W);
- ψ_j : Power consumption for a MAP in site j (18 W);
- $\delta(t)$: Duration of time period t;
- β : Objective function trade-off parameter;
- $\eta_{1,2}$: Maximum number of times that a MR/MAP can switch from on to off state (or vice versa), both set to 1 for all the presented examples;
- a_{ij} : Binary, equal to 1 if MC i is covered by the BS in site j;
- b_{jl} : Binary, equal to 1 if a wireless link between BSs in sites j and l is possible.

Variables

- z_j : Binary, equal to 1 if a MR is installed in site j;
- w_j : Binary, equal to 1 if a MAP is installed in site j;
- y_{jt} : Binary, equal to 1 if the MR in site j is active;
- r_{jt} : Binary, equal to 1 if the MAP in site j is active;
- v_{jt} : Binary, equal to 1 if the MR in site j switches state from time $t-1$ to time t;
- g_{jt} : Binary, equal to 1 if the MAP in site j switches state from time $t-1$ to time t;
- x_{ijt} : Binary, equal to 1 if MC i is assigned to a BS installed in site j in period t;
- k_{jl} : Binary, equal to 1 if there is a wireless link between the BSs in sites j and l;
- f_{jlt} : Flow between the BSs in sites j and l in period t;
- f_{jIt} : Flow between the MAP in site j and Internet in period t.

2.3 The reference model

The joint design and management model for WMNs ($P0$) is defined as follows.

Objective function

$$\begin{aligned} \min \quad & \beta \sum_{j \in S} (z_j \gamma_j + p_j w_j) + \\ & + (1-\beta) \sum_{j \in S} \sum_{t \in T} (\epsilon_j y_{jt} + \psi_j r_{jt}) \delta(t) \end{aligned} \tag{1}$$

The objective function (1) is composed of a first term, representing the installation cost for the selected BSs (*Capex*, Capital Expenditures), and a second term that expresses the power consumption of the active devices in any time period. The trade-off parameter β varies in the $[0, 1]$ interval and is used to adjust the weight of the Opex term with respect to the Capex one.

Constraints

$$z_j + w_j \leq 1 \qquad \forall j \in S \tag{2}$$
$$y_{jt} \leq z_j \qquad \forall j \in S, t \in T \tag{3}$$
$$r_{jt} \leq w_j \qquad \forall j \in S, t \in T \tag{4}$$

Constraints (2) indicate that there must be at most one device (MR or MAP) installed in every site, while (3) and (4) allow the activation of a MR/MAP during any time interval only when the device has been actually deployed.

$$\sum_{i \in I} x_{ijt} d_{it} \leq c_j (y_{jt} + r_{jt}) \qquad \forall j \in S, t \in T \tag{5}$$

(5) impose that the total traffic requirement of the users assigned to a BS does not surpass the BS capacity.

$$\sum_{l \in S} (f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it} x_{ijt} = f_{jNt} \qquad \forall j \in S, t \in T \tag{6}$$
$$f_{ljt} + f_{jlt} \leq u_{jl} k_{jl} \qquad \forall j, l \in S, t \in T \tag{7}$$
$$f_{jNt} \leq m r_{jt} \qquad \forall j \in S, t \in T \tag{8}$$

Constraints (6) guarantee the flow conservation for a BS in site j. (7) set the maximum traffic amount that can be routed by each existing link and (8) limit the capacity of the MAPs Internet access to m, while the flow toward the backbone is forced to zero if the device in site j is a MR.

$$k_{jl} \leq z_j + w_j \qquad \forall j, l \in S \tag{9}$$
$$k_{jl} \leq z_l + w_l \qquad \forall j, l \in S \tag{10}$$
$$k_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{11}$$
$$f_{ljt} + f_{jlt} \leq u_{jl} (y_{jt} + r_{jt}) \qquad \forall j, l \in S, t \in T \tag{12}$$
$$f_{ljt} + f_{jlt} \leq u_{jl} (y_{lt} + r_{lt}) \qquad \forall j, l \in S, t \in T \tag{13}$$

The existence of a wireless link between two BSs is allowed in case they are active ((9) and (10)) and neighbors ((11)). Also, (12) and (13) enable the use of the link (l, j) only if BSs in sites j and l are turned on.

$$\sum_{j \in S} x_{ijt} = 1 \qquad \forall i \in I, t \in T \tag{14}$$
$$x_{ijt} \leq a_{ij} (y_{jt} + r_{jt}) \qquad \forall i \in I, j \in S, t \in T \tag{15}$$

Assignment constraints impose that every customer is assigned to a single BS ((14)) and only if the BS is active and covers it ((15)).

$$y_{J_l^{(i)} t} + r_{J_l^{(i)} t} + \sum_{h=l+1}^{l_i} x_{i J_l^{(i)} t} \leq 1 \quad \forall i \in I, t \in T, l : 1 \ldots B_i - 1 \tag{16}$$

Constraints (16) state that every user must be served by the most suitable BS in relation to an ideal parameter, such as the mutual distance or the received signal strength.

$$v_{jt} \geq y_{jt} - y_{jt-1} \qquad \forall j \in S, t \in T/\{t_1\} \tag{17}$$
$$v_{jt} \geq y_{jt-1} - y_{jt} \qquad \forall j \in S, t \in T/\{t_1\} \tag{18}$$
$$g_{jt} \geq r_{jt} - r_{jt-1} \qquad \forall j \in S, t \in T/\{t_1\} \tag{19}$$
$$g_{jt} \geq r_{jt-1} - r_{jt} \qquad \forall j \in S, t \in T/\{t_1\} \tag{20}$$

The value of the auxiliary variables v_{jt} and g_{jt} is set to 1 if the MR ((17) and (18)) or the MAP ((19) and (20)) installed in j changes state from time $t-1$ to time t. Constraints (17) and (18) replace the non linear expression $v_{jt} \geq |y_{jt} - y_{jt-1}|$, while (19) and (20) linearize constraints $g_{jt} \geq |r_{jt} - r_{jt-1}|$.

$$\sum_{t \in T/\{t_1\}} v_{jt} \leq \eta_1 \qquad \forall j \in S \tag{21}$$

$$\sum_{t \in T/\{t_1\}} g_{jt} \leq \eta_2 \qquad \forall j \in S \tag{22}$$

These constraints state that each MR ((21)) or MAP ((22)) can change its state at most, respectively, η_1 or η_2 times.

$$x_{ijt}, y_{jt}, r_{jt}, z_j, w_j, k_{jl} \in \{0,1\} \quad \forall i \in M, j, l \in S, t \in T \tag{23}$$
$$v_{jt}, g_{jt} \in \{0,1\} \quad \forall j \in S, t \in T/\{t_1\} \tag{24}$$

Finally, (23) and (24) are binary constraints.

3 Resolution approach and problem variations

The mathematical model presented in Section 2.3 has been developed with the AMPL programming language and optimized using the CPLEX solver. An instance generator was created to produce three realistic WMN test scenarios: the *small* scenario presents 40 MCs and 16 CSs over a square area of 1 km^2, the *medium* scenario includes 130 MCs and 40 CSs over a square area with side 1.5 km and the *large* scenario has 240 MCs and 64 CSs placed over a square area with side 2.5 km.

In order to prove the soundness of our study and compare our results in different conditions, four variations of the problem $(P0)$ have been tested.

3.1 The cellular comparison

We assume that only gateways (MAPs) can be installed. This case represents a *cellular network*, where every BS is directly connected to the backbone and forwards the traffic towards the Internet without any intermediate hop. This *MAPs only* scenario aims at quantifying the benefits in terms of energy savings that can be obtained by deploying and operating a WMN instead of a cellular network.

3.2 The two-step approach

Here, the energy management model proposed in [14] is applied to a pre-determined network design, which is directly obtained from $(P0)$ by setting $\beta = 1$ for minimizing the capital expenses. By comparing the original model results with the ones given by the *two-step* optimization, where the network design is determined first and only then an energy management model is applied, our objective is to underline the influence of a combined approach on both network topology and network power consumption.

3.3 The on/off switching constraints relaxation

By relaxing constraints (17) to (22) in ($P0$), we derive problem ($P1$) in which every installed BS is allowed to change its state (from on to off or vice versa) as many times as required by the model for minimizing Opex. Hence, results from ($P0$) and ($P1$) will be compared.

3.4 The partial coverage problem

In the fourth test we show another relaxed variation of the reference model, which aims at providing network services only to active clients in each time period. In this case, those BSs having only idle users in their covering ray can be turned off. To formulate the *partial coverage problem* ($P2$) we introduce a new binary parameter h_{it} that is equal to 1 if the MC i is providing traffic in period t. Also, the network service can be limited only to active users replacing constraints (15) of ($P0$) by:

$$h_{it}x_{ijt} \leq a_{ij}(y_{jt}+r_{jt}) \quad \forall i \in M, j \in S, t \in T \tag{25}$$

Then ($P2$) can be written as:

$$\begin{aligned} \min \quad & (1) \\ \text{s.t.} \quad & (2) \text{ to } (14), (25), (16) \text{ to } (24). \end{aligned}$$

Concerning computation times, they range from a few seconds to approximately 1 hour for ($P0$) and ($P1$), reaching an optimality gap lower than 1%, while the partial coverage problem ($P2$) is solved in up to 13 hours (*large* scenario) by setting the maximum gap at 4%. On the other hand, solving times are minimal in case of *MAPs only* or *two-step* approaches.

4 Numerical results

4.1 The reference model ($P0$)

In this section we show selected results from a large set of instances for the main problem and its variations. Table 1 gathers the percentages of energy savings achieved by using the basic joint design and management model ($P0$) and its relaxed versions ($P1$) and ($P2$). Each entry corresponds to a particular value of the trade-off parameter applied to the test scenarios described in Section 3. Except for the ones in brackets, the percentages refer to the energy requirement of the same test scenarios when β is set to 1. In such a case, since operational issues are ignored, the model provides a simple network design optimization and all the

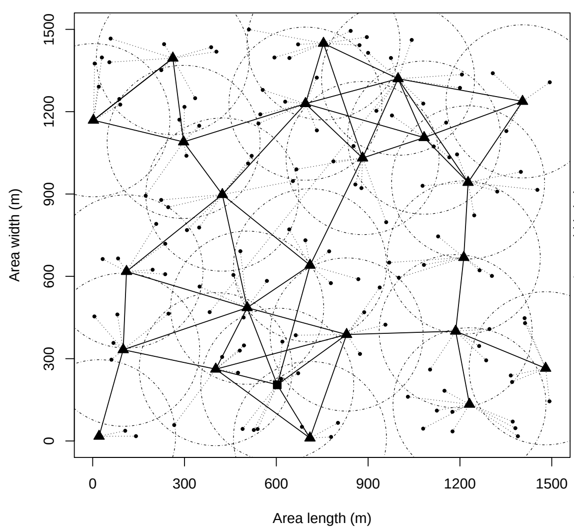
Table 1: Energy saving obtained from ($P0$), ($P1$) and ($P2$).

		$\beta = 0.8$	$\beta = 0.5$	$\beta = 0.1$
($P0$)	Small	15.37%	20.50%	23.77%
	Medium	7.75%	10.33%	14.67%
	Large	12.12%	12.40%	15.46%
($P1$)	Small	20.49% *(+6.05%)*	27.66% *(+9.17%)*	27.66% *(+5.10%)*
	Medium	12.39% *(+5.04%)*	14.98% *(+5.18%)*	20.87% *(+7.26%)*
	Large	17.94% *(+6.62%)*	20.80% *(+9.59%)*	23.11% *(+9.05%)*
($P2$)	Small	10.65% *(+7.26%)*	10.65% *(+1.43%)*	16.36% *(+3.60%)*
	Medium	14.46% *(+7.28%)*	14.46% *(+4.61%)*	20.97% *(+6.24%)*
	Large	13.20% *(+1.23%)*	13.47% *(+1.23%)*	20.04% *(+5.42%)*

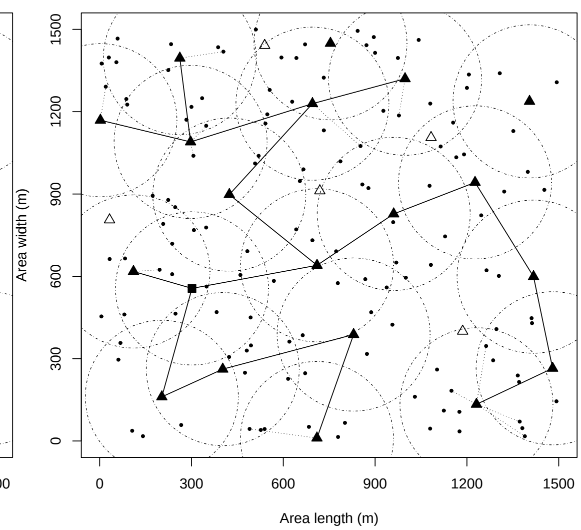
installed BSs are constantly switched on. The percentages reported in parenthesis for ($P1$) and ($P2$) are calculated with respect to the results obtained by applying ($P0$) to the same scenario with the same value of β and express the additional savings that can be reached by guaranteeing the network coverage only to active users.

Observe the ($P0$) section of Table 1. When the trade-off parameter β decreases, the proposed model is pushed to optimize the network topology and operation in a joint way. For this, just enabling the energy management mechanism by setting β to 0.8 leads to daily power savings of more than 15%, since only those BSs that are necessary for covering all the MCs are turned on.

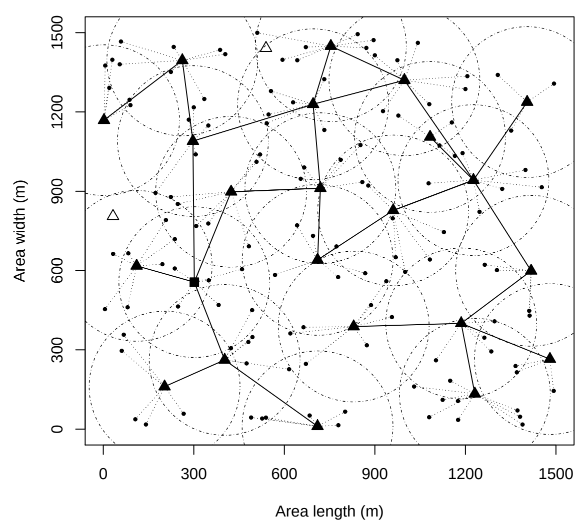
To better envision the network design variations, in Figure 1 we reported some significant configurations obtained for the *medium* scenario. Every subfigure corresponds to certain values of β and time periods (the lowest- and the highest-traffic ones, t_2 and t_4). Active MRs and MAPs are represented by black triangles and squares respectively, while idle ones by the same white symbols. Mesh users are depicted as black dots and each of them must reside at least in one BS coverage area, represented in the pictures by a dotted circumference centered in each active BS location. Also, the MCs providing traffic are connected by dotted



(a) $\beta = 1$, t_2 *and* t_4*: 23 MRs, 1 MAP.*



(b) $\beta = 0.5$, t_2*: 19 MRs, 1 MAP.*



(c) $\beta = 0.5$, t_4*: 22 MRs, 1 MAP.*

Figure 1: ($P0$), *medium* scenario. Network design and behavior for different values of β and time periods.

lines to the BSs they are assigned to. Finally, the network structure is revealed by black lines representing wireless links between MRs and MAPs.

Figure 1a displays the topology obtained for $\beta = 1$, when only capital costs are minimized. The picture refers in particular to peak-traffic period t_4, since all mesh clients are active and connected to a BS, but the same activation pattern applies to all time periods. As no energy management is enabled, even in t_2, when only 12 MCs are providing traffic, so much as 23 MRs are turned on, while the overlap between the coverage areas would permit to turn off some of them. On the other hand, when $\beta < 1$, only the routers that are really required to serve active MCs or cover the service area are turned on. Taking as example the solution obtained for $\beta = 0.5$, 19 MRs in period 2 (Figure 1b) and 22 MRs in period 4 (Figure 1c) are enough to satisfy the coverage constraints. Therefore, the power management mechanism allows energy savings of more than 10% compared to the previous case.

4.1.1 The cellular comparison

Tables 2 and 3 show in more detail how ($P0$) and the *MAPs only* approach behave when applied to the medium size test scenario. The rows of the first table display, respectively, the values of capital expenditures (Capex, expressed in Euro), the daily energy requirements (expressed in kiloWatt per hour) and the number of installed routers (MRs) and gateways (MAPs). The percentages in italics show the savings with respect to the case of $\beta = 1$. Every column, except for the "2-step" one (that will be explained in the next subsection), reports results for different values of β. As β decreases, the energy savings progressively grow and changes in the network deployment can also be observed (different number of installed MRs and MAPs). Concerning the *MAPs only* approach, by reproducing a purely cellular network we can evaluate the improved power efficiency provided by the adaptability of WMNs. In Table 3 we present in bold the percentage variation in Capex and energy expenditures with respect to the corresponding values in Table 2. Notably, both installation costs and power expenditures face a sensible increase, due to the fact that only the most power consuming devices can be deployed and thereby the flexibility typical of mesh networking cannot be exploited. Despite that, the joint approach still guarantees energy savings of 13% for $\beta = 0.5$ with 4% extra Capex and 14.56% for $\beta = 0.1$.

Table 2: *(P0)*, *medium* scenario. Summary of the results with different values of β.

	$\beta = 1$	**2-step**	$\beta = 0.5$	$\beta = 0.1$
Capex (k€)	5.00	5.00	5.20	6.40
Energy (kWh/d)	8.71	8.44	7.81	7.43
	-	*-3.10%*	*-10.33%*	*-14.67%*
Installed MRs	23	23	24	26
Installed MAPs	1	1	1	3

Table 3: *MAPs only* approach, *medium* scenario. Summary of the results with different values of β.

	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
Capex (k€)	9.60	10.00	10.40
Capex - vs ($P0$)	**+92.00%**	**+92.31%**	**+62.50%**
Energy (kWh/d)	10.37	9.02	8.86
	-	*-13.02%*	*-14.56%*
Energy - vs ($P0$)	**+19.06%**	**+15.49%**	**+19.25%**
Installed MAPs	24	25	26

4.1.2 The two-step approach

As introduced in Section 3, we want to underline further the benefits of the joint approach by comparing the power savings with the ones obtained with the optimal energy operation of a previously, well designed network. Note that, differently from the proposed model, since the two optimization problems (network design and energy management) are independent, in case of a two-step procedure we cannot adjust the importance of Opex with respect to Capex according to any particular network need. In Table 2, column “2-step”, the results for the *medium* scenario are provided together with the results obtained by applying the reference model. The advantages of the proposed joint framework are evident when observing subsequently the numbers found for $(P0)$ and the ones got by using the *two-step* approach. For example, if $\beta = 0.5$, the energy savings given by the *two-step* approach are more than tripled at the cost of a slight increase (+4%) in Capex expenses. Similarly, almost 12% of the power can be saved by investing the 28% more in the installation phase for $\beta = 0.1$. Hence, our joint model does not restrict itself to decrease the power expenses of the minimum cost topology, but it trades off between the two terms of the objective function to find the best compromise of energy savings and installation costs reduction. Concerning this, it must be taken into account that, even if Capex costs seem high compared to savings related to the power management, deployment expenses incur only once while energy savings are spread during the whole network life. Always taking the case of $\beta = 0.5$ as example, the additional initial investment of 200 € can be recovered from the energy savings in less than one year of network operation (230 €/year spared), which is a short period compared to the average network life. Furthermore, if $\beta = 0.1$, one can estimate that the extra 1400 € needed for deploying the chosen topology correspond to the power savings that could be reached in about four years (369 €/year saved).

4.2 The on/off switching constraints relaxation $(P1)$

In order to show how the network topology and management differ when installed BSs are allowed to freely turn on and off, we report in Table 4 the results obtained by solving problem variation $(P1)$ for the *small* scenario. As for Table 3, the further energy savings obtained with respect to the ones found in case of $(P0)$ for the same scenario are presented in bold.

Table 4: $(P1)$, *small* scenario. Summary of the results with different values of β.

	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
Capex (k€)	2.60	2.80	2.80
Capex - vs $(P0)$	**-0%**	**-0%**	**-12.5%**
Energy (kWh/d)	4.39 -	3.17 *-27.66%*	3.17 *-27.66%*
Energy - vs $(P0)$	**-0%**	**-9.17%**	**-5.10%**
Installed MRs	11	12	12
Installed MAPs	1	1	1

In this case, the relaxation of the state switching constraint does not bring any modification to the network topology when $\beta = 0.5$ (Capex costs remain unchanged), while, if $\beta = 0.1$, $(P1)$ allows 12.5% savings in capital expenses. Concerning the energy issue, the relaxed model reaches 5%-10% lower power consumptions compared to the reference model: this outcome was expected, since $(P1)$ deploys a more flexible network topology, where only the BSs that are indispensable for routing the traffic or covering the service area are maintained in the on state.

4.3 The partial covering problem $(P2)$

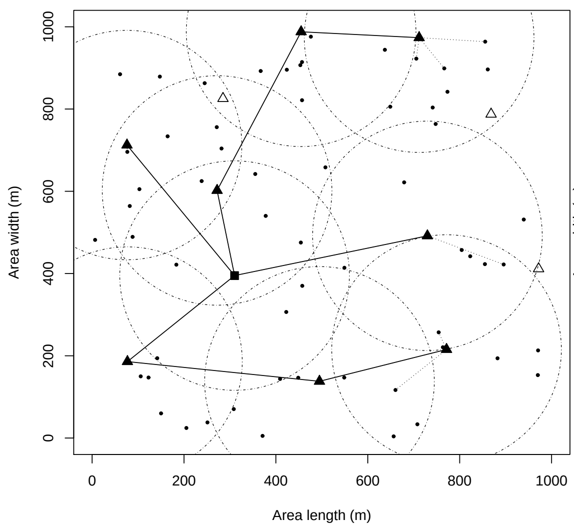
The results computed for the *small* scenario by applying the partial covering problem $(P2)$ are shown in Table 5. Again, percentages in bold represent the additional energy savings achieved with reference to $(P0)$ results for the same scenario.

As already pointed out, important energy savings can be achieved when installation and management costs are optimized in a joint way. For instance, when $\beta = 0.1$, the power consumption is reduced by more than 16% by installing one more MR and one more MAP at the extra cost of 600 €. Predictably, since the network service must be guaranteed only for active users, the relaxed formulation $(P2)$ acts as the reference model but it allows slightly higher energy savings with respect to $(P0)$. Note that the low values of the saving percentages are mostly due to constraints (21) and (22), which limit to 1 the maximum number of times each BS can change its on/off state. Finally, in Figure 2 it is possible to observe the effects of the network

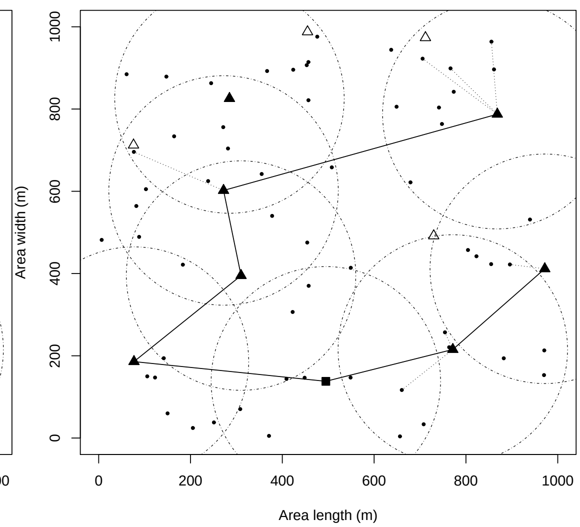
Table 5: $(P2)$, *small* scenario. Summary of the results with different values of β.

	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
Capex (k€)	2.60	2.60	3.20
Capex - vs $(P0)$	**-0%**	**-7.14%**	**-0%**
Energy (kWh/d)	3.85	3.44	3.22
	-	*-10.65%*	*-16.36%*
Energy - vs $(P0)$	**-12.30%**	**-1.43%**	**-3.60%**
Installed MRs	11	11	12
Installed MAPs	1	1	2

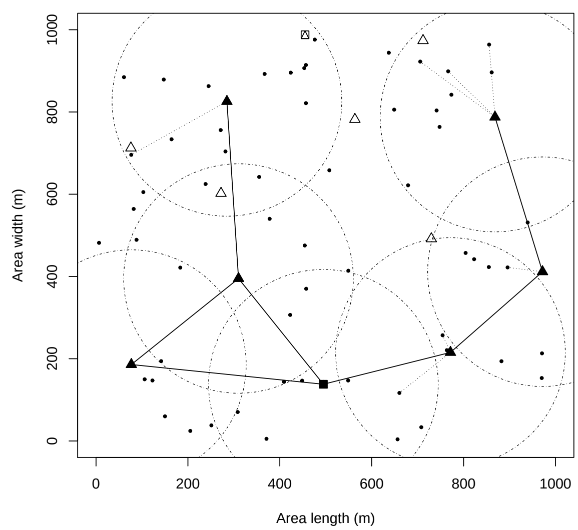
management performed by $(P2)$ in order to minimize the total power consumption when the full coverage constraints are relaxed.



(a) $\beta = 1$, t_2: *8 MRs, 1 MAP.*



(b) $\beta = 0.5$, t_2: *7 MRs, 1 MAP.*



(c) $\beta = 0.1$, t_2: *6 MRs, 1 MAPs.*

Figure 2: $(P2)$, *small* scenario. Network design and behavior for different values of β in time period t_2.

5 Conclusion

In this paper we developed an optimization approach for Wireless Mesh Networks that jointly selects the access devices to be installed and controls their energy-aware operation. By mean of three test scenarios, we have shown that the minimum cost topology does not guarantee a power-efficient operation; on the contrary, the highest energy savings are achieved when network planning and management are handled at the same time. We confirmed the benefits of our framework by comparing our results with the ones obtained from a traditional two-step approach, where network planning and energy-aware operation are optimized separately. Also, we analyzed the energy savings reached when the total area coverage constraints are relaxed, highlighting the fundamental role of the network coverage flexibility to reduce power consumption.

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