Les Cahiers du GERAD ISSN: 0711–2440

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G–2011–96

December 2011

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Abstract

This paper deals with the joint planning and energy management operation of Wireless Mesh Networks. We claim that energy management should be incorporated at the planning stages to produce an effective energy-management operation. For this, we propose a mathematical framework that takes into account the trade-off of capital expenditures versus energy-related operational ones when designing the network. We also present results that put into relevance the impact of different coverage policies on energy efficiency.

Key Words: Energy Efficiency, Mesh Networks, Wireless Network Planning, Network Operation, Green Networking, Joint Planning and Energy Management, Network Design.

1 Introduction

The debate on global warming and energy efficiency in ICT is becoming increasingly important. There is now evidence [1], that the ICT industry has a significant part of responsibility for the global carbon emissions, with telecommunications networks (including mobile, WLANs, LANs and wired networks) representing almost 50% of ICT power expenditures [2].

The answer of the research community has been *green networking*, consisting on a new way of building and managing telecommunications networks to reduce their energy needs. As a matter of fact, it is clear that working towards the so-called green networks is not only profitable in terms of the cost savings related to power expenses (*Opex*, Operational and Management Expenditures), but also allows the deployment of networks having low environmental impact.

Among the network segments, the access is the one with the major influence on energy consumption, being liable for 80% of the overall power expenditures [3, 2]. This is mostly because Wireless Access Networks (WANs) are usually dimensioned to satisfy the quality constraints under peak traffic conditions, resulting in over-provisioning in low-demand periods thus wasting a significant amount of power. From this point of view, trying to minimize the energy consumption of deployed access elements (that is to say, base stations) is an important goal.

There has been interesting models and approaches to deal with the problem of power savings in both wireless and wired networks [4]. Nevertheless, a fundamental issue that has been overlooked is that an effective energy-aware operation is closely dependent on the *planning* decisions taken during the network design phase. In other words, we claim that when the network is designed with the classical cost-performance trade-off, the energy management operation would be less efficient than if energy management is directly incorporated at the planning stages. To the best of our knowledge, the only example of this kind of analysis can be found in our previous work [5], where the significant advantages of jointly optimizing network design and operation in cellular networks are evaluated.

Differently from [5], we focus here on Wireless Mesh Networks (WMNs), a newly emerged type of access network offering wireless connectivity with the use of cheap and low transmission power devices. WMNs are dynamically self-organized and self-configured communication infrastructures, with a high degree of co-operation between many individual wireless stations. Each node works not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct transmission range of their destinations. Thus, the nodes automatically establish mesh connectivity among themselves, creating in effect an ad hoc network [6]. However, as usually happens in the other types of access networks, WMNs infrastructure devices are always active. Thus, during lower traffic periods the energy consumption is the same as in busy hours, while it would be possible to save a large amount of power by turning off unnecessary nodes. Concerning this issue, an energy-aware approach for such kind of networks was tackled in [7], where the power expenses of a deployed network were minimized by dynamically selecting a subset of base stations to be switched on. However, that article did not consider energy management jointly with network planning but as a purely operational feature.

The question that we want to answer in this paper is given the highly adaptive features of Mesh Networks, to what extend the philosophy of jointly planning and energy optimization yields important energy efficient results. For this, we will proceed to present a mathematical framework and extensive results to seize the advantage of this type of approach for Wireless Mesh green networking.

The reminder of the paper is structured as follows. In Section 2 we present an overview on related work. Section 3 provides a description of the Wireless Mesh system and gives an overview of planning and operational models that are important preliminaries to understand the joint optimization framework that is presented in Section 4. The resolution approach is presented in Section 5, where we also explain the model variations used for testing the effectiveness of our optimization method. Numerical results are fully commented in Section 6, while Section 7 concludes the paper

2 Related work

Several studies on green networking have appeared in the last few years, starting from the seminal work of Gupta and Singh [8]. A complete overview of the main research ideas on this topic can be found in [9] and [4], where the authors survey different proposals for reducing the power consumption in both wired and wireless networks.

Despite the fact that wireless systems have high responsibility in the increase of power expenditures, most of the work on infrastructure consumption have focused on wired networks. However, wireless research has always been involved in energy-related problems given the mobile nature of the network devices that is pushing for improvements in batteries life and coverage techniques. Therefore, the literature includes many studies on energy-efficient *devices* [10, 11] and *protocols* [12] for WLANs and cellular networks (for an excellent review, see [13]). On the other hand, the interest in infrastructure wireless green networking design and operation has only started in recent years and deals more with *management* than with planning issues.

For instance, concerning WLANs, in [14] and [15] the Resource on Demand (RoD) approach is proposed, aiming at powering off some access points during off-peak traffic periods following real-time traffic variations or fixed pre-determined schedules. The system behavior under two different RoD strategies is evaluated in [16]. Considering cellular networks, several works assess the possibility of switching off some nodes when they are underutilized, based on average measurements of traffic exchange between nodes [17] or deterministic traffic variations during the day [18]. In our previous work [5], for the first time the energy expenses problem is tackled from a dual standpoint: given that an effective energy-aware network operation closely depends on the locations chosen for the network devices, we develop a joint design and management model that aims at limiting both energy consumption and operational expenditures.

Concerning WMNs in general, previous work concentrates mainly on MAC and routing protocols, mobility management and security topics. Most of the time, the network topology (that is to say, the positions of routers and gateways) was pre-established and the goal was to optimize the routing or the channel assignment. Few authors have investigated the problem of planning wireless mesh access networks. In [19], a single pre-installed access point is considered and only the positions of routers are optimized, while in [20] and [21] the authors formulate a modeling approach for locating gateways given the locations of the other nodes. A mathematical model for the complete WMN design is proposed in [22], where the number and positions of mesh routers and access points are to be selected, always taking into account typical network issues such as traffic routing and channel assignment. In the context of green networking, an energy-aware management for WMNs is obtained in [7] where starting from a previously deployed network, the authors try to minimize the power consumption in a time varying context by dynamically turning on and off some base stations (routers or access points) (see Section 3.3.2 for more details on the models presented in [22] and [7]).

A very interesting framework is presented in [23] where four fundamental trade-offs for an effective green network are stated and an excellent overview of the current and future studies in green networking research area is presented. Moreover, the exhaustive analysis of the Deployment Efficiency – Energy Efficiency (DE-EE) trade-off reported in [24] is a good starting point to better understand the importance and complexity of the issue we tackle in this paper.

Differently from the aforementioned papers, we present the following original contributions:

- We propose the joint optimization of the planning and energy-aware operation for Wireless Mesh Networks and create, for the first time, a rigorous optimization model.
- We compare the savings obtained with the joint planning and operation framework philosophy with the one obtained when planning and energy aware operation are performed in separate stages.
- We compare the energy savings obtained for Mesh and cellular networks obtained with the same type of modeling philosophy.
- We study the effect of different planning and operating coverage strategies on overall network consumption.

3 System description and preliminary mathematical models

The philosophy of the modeling framework that will be presented in Section 4 is based on exploiting the dynamic features of WMN to design a system that is not only cost-effective, but also follows the demand in an energy-efficient way during normal operation. In order to follow the demand, we must first characterize it by time periods and the energy management framework will consist in deciding which device should be put down during the daily operation to minimize energy consumption. As the model is jointly a planning and an operational one, the framework idea is to choose, at the same time, the network configuration and the operational features.

In the rest of this section, we first provide an overview of the WMN system description. Next, we discuss how traffic variations are characterized. The last subsection is devoted to revisiting the planning and operational models that have been previously presented and that are necessary to understand our joint planning and operation proposal of Section 4.

3.1 System description

Wireless Mesh Networks are made up of two types of fixed elements, Mesh Routers (MRs) and Mesh Access Points (MAPs), forming the mesh backbone for mobile users, named Mesh Clients (MCs). From now on, when generally referring to MRs and MAPs the term Base Stations (BSs) will be used. Both kinds of BSs have the task of setting up a Wireless Distributed System (WDS) by connecting to other mesh routers and access points through point to point wireless links while providing network access for the MCs. In addition, MAPs, representing only a restricted set of routers, behave as gateways toward the wired backbone, enabling the integration of WMNs with other networks (typically the Internet).

In developing our WDS, we follow the assumptions made in [7]. MRs and MAPs that reside in the respective covering ray can communicate through dedicated wireless channels, each one having bidirectional capacity unvarying with the distance. We admit that the traffic in a link does not affect closer links since all devices are equipped with multiple network interfaces. Concerning MCs, they can be assigned to a BS only if they are included in a circular cell centered in the BS and having a ray of $250\,m$. Moreover, mesh users are served by the nearest active router and are connected to the Internet through multi-hop communications.

In terms of numerical values, we use the Wi-Fi 802.11n standard for communication between routing devices, with a nominal link capacity of $450\,Mbps$ and a coverage ray of $450\,m$. Note that the coverage ray between two BSs is almost doubled with respect to the one between BSs and MCs since directive antennas are used for connecting MRs and MAPs in order to limit unwanted interference. Finally, the access technology Wi-Fi 802.11g with $54\,Mbps$ is chosen, shared among all users assigned to a BS.

3.2 Traffic variations pattern

Different studies have dealt with traffic variations measurement in Wireless Access Networks [25, 26]. Considering an approximated traffic profile based on these studies, in [27], [5] and [7] the authors split the whole day into time periods in order to take into account the demand fluctuations in WLANs, cellular or mesh networks, respectively. By dividing the day into smaller intervals in which users behavior is assumed unchanged, the on-off operation of the access network will allow following the traffic variations and reducing power consumption of unneeded devices.

Let T be the ordered set of time periods displayed in Table 1. Note that no time gap is admitted between adjacent intervals, and the summed duration of all intervals is equal to the number of hours in a day. A value ρ_t is assigned to each time period, representing the probability that an MC provides traffic to the network. In other words, ρ_t is the *percentage of active users* typical of every time interval.

As presented in [7], two different degrees of congestion have been tested:

- *Standard profile*, in which active MCs provide a traffic amount randomly generated between 1 and $10\,Mbps$;
- *Busy profile*, in which the demand of active users varies from 8 to $10\,Mbps$.

Table 1: Time periods and demand variations during a day.

Index	1	2	3	4	5	6	7	8
Start	00:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00
End	3:00	6:00	9:00	12:00	15:00	18:00	21:00	24:00
Duration	3 h	3 h	3 h	3 h	3 h	3 h	3 h	3 h
ρ_t	0.35	0.1	0.45	1	0.7	0.85	0.6	0.5

3.3 Basic approaches to network planning and energy management

Before introducing our joint network design and management model (in Section 4) we briefly present the two mathematical programming models representing the basic approaches to the separate problems of WMNs planning [22] and WMNs energy management [7]. Note that the original notation was changed for commonality in model description.

3.3.1 WMNs network planning

The general idea of the formulation presented in [22] is deciding where and what kind of access devices should be installed in order to satisfy the users demand and minimize Capex costs. Let S be the set of Candidate Sites (CSs) available to host a MR or a MAP and let I be the set of MCs, each one providing a constant traffic value defined by $d_i, i \in I$. Let N be a special node representing the Internet. Moreover, the set $J_h^{(i)}$ is required to recognize the most convenient BSs for every MCs: it represents the subset of BSs covering user i, ordered by decreasing received power.

Two are the required binary parameters: a_{ij} is equal to 1 if MC i is covered by the BS located in site j, while b_{jl} is equal to 1 if a wireless link can be installed between the BSs in sites j and l.

The binary decision variables x_{ij} are used to assign MC i to the BS located in j, the installation variables z_j indicate wether CS j is chosen in the solution, variables w_j show if a MAP is installed in site j and variables k_{jl} define if the BSs located in j and l are connected through a wireless link. Additional integer variables f_{jl} represent the traffic on wireless link (j,l), while f_{jN} is the flow from the MAP in site j to the Internet.

The mathematical model of the WMN design problem is the following:

$$\min \quad \sum_{j \in S} (z_j \gamma_j + p_j w_j) \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in S} x_{ij} = 1 \qquad \forall i \in I \tag{2}$$

$$x_{ij} \leq a_{ij} z_j \qquad \forall i \in I, j \in S \tag{3}$$

$$\sum_{l \in S} (f_{lj} - f_{jl}) + \sum_{i \in I} d_i x_{ij} = f_{jN} \qquad \forall j \in S \tag{4}$$

$$f_{lj} + f_{jl} \leq u_{jl} k_{jl} \qquad \forall j, l \in S \tag{5}$$

$$f_{jN} \leq m w_j \qquad \forall j \in S \tag{6}$$

$$\sum_{i \in I} x_{ij} d_i \leq c_j \qquad \forall j \in S \tag{7}$$

$$k_{jl} \leq z_j, \quad k_{jl} \leq z_l \qquad \forall j, l \in S \tag{8}$$

$$k_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{9}$$

$$z_{J_l^{(i)}} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}} \leq 1 \qquad \forall i \in I, l : 1 \ldots B_i - 1 \tag{10}$$

$$x_{ij},\, z_j,\, k_{jl},\, w_j \in \{0,1\} \qquad \forall i \in I, j, l \in S \tag{11}$$

Objective function (1) minimizes the network deployment costs, given by a basic installation cost γ_j common to all BSs located and additional costs p_j due to the connection of MAPs to the Internet. Constraints (2) and (3) insure that each MC is assigned to a BS that covers it. (5) are flow balance equations, while (6), (7) and (8) are capacity constraints for links, MRs and MAPs respectively. Constraints (8) and (9) guarantee that a link is installed only if the two involved nodes are both active and neighbors, while (10) force the assignment of every MC to the nearest installed BS. Finally, constraints (11) impose binary values for some decision variables.

Notably, this formulation does not take into account any network operation or energetic aspect and no demand variations over time are considered. These will be taken into account in the next subsection.

3.3.2 WMNs energy management

The model revisited here was formulated in [7]. Given an existing network, the problem is that of deciding which BSs should be switched off according to the variations of the users traffic profiles. In addition to the two sets previously defined, let T be the set of time intervals described in Table 1 and let $G \subseteq S$ the subset of BSs that are MAPs.

Since the traffic offered by users is different depending on the time intervals, an extended traffic matrix d_{it} is defined. The assignment of MCs can now change in time, so that decision variables x, f and f_N are now identified by one more index t. Another group of variables, y_{jt}, is introduced to indicate if the BS located in j is active at time t.

The WMNs energy management formulation is the following:

$$\min \quad \sum_{j \in S} \sum_{t \in T} \epsilon_j z_{jt} \Delta(t) \tag{12}$$

$$\text{s.t.} \quad \sum_{j \in S} x_{ijt} = 1 \qquad \forall i \in I, t \in T \tag{13}$$

$$x_{ijt} \leq a_{ij} z_{jt} \qquad \forall i \in I, j \in S, t \in T \tag{14}$$

$$\sum_{l \in S} (f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it} x_{ijt} = f_{jNt} \qquad \forall j \in S, t \in T \tag{15}$$

$$f_{ljt} + f_{jlt} \leq u_{jl} b_{jl} z_{jt} \qquad \forall j, l \in S, t \in T \tag{16}$$

$$f_{jNt} \leq m \qquad \forall j \in S, t \in T \tag{17}$$

$$\sum_{i \in I} x_{ij} d_i \leq c_j \qquad \forall j \in S, t \in T \tag{18}$$

$$z_{J_l^{(i)}} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}} \leq 1 \qquad \forall i \in I, l : 1 \ldots B_i - 1 \tag{19}$$

$$x_{ij},\, z_j \in \{0, 1\} \qquad \forall i \in I, j, l \in S \tag{20}$$

Here the objective function (12) aims at minimizing the sum of BSs energy consumption ϵ_j over all time periods. As for the previously described model, (13) and (14) are assignment constraints, (15) are flow balance constraints and (16), (17) and (18) are capacity constraints for links, MAPs Internet access and BSs. Finally, constraints (19) guarantee the best possible assignment for every user. Constraints (20) impose binary values to the decision variables.

4 Joint network design and management for WMNs

In the previous section, we revisited, respectively, a planning and energy management model for WMN. In this section, we present a joint planning and management optimization approach based on the modeling philosophy proposed in [5] for cellular networks that combines the minimization of installation costs and the maximization of energy savings. This way we strive to underline the tight relationship existing between an effective energy-aware network operation and wise decisions made during planning phases. We now present the notational framework, a reference model as well as some key relaxations that will be used for comparison purposes in the results section.

4.1 Notational framework

To be able to set the mathematical model, we need an additional notation. For the sake of completeness, some of the notation that was first presented in Section 3.3 is also included here.

Sets

I : Set of MCs generating variable traffic;

S : Set of the available CSs for the BSs;

T : Set of time intervals;

$J_h^{(i)}$: Subset of BSs covering MC i, ordered by descending received power.

Parameters

d_{it} : Traffic provided by MC i in period t;

c_j : Access capacity of the BS located in site j;

u_{jl} : Capacity of the wireless link between BSs located in sites j and l;

m : Capacity of the MAPs Internet access;

γ_j : Installation cost for a MR located in site j;

p_j : Installation cost for a MAP located in site j (it includes the cost for connecting the MAP with the wired backbone);

ϵ_j : Power consumption for a MR located in site j;

ψj : Power consumption for a MAP located in site j;

B_i : Number of BSs covering TP i;

$\Delta(t)$: Duration of time period t;

β : Weight parameter used for trading-off the objective function.

a_{ij} : Equal to 1 if TP i is covered by a BS installed in j, 0 otherwise;

b_{jl} : Equal to 1 if a wireless link between BSs located in sites j and l is possible, 0 otherwise.

Variables

$$z_j = \begin{cases} 1 & \text{if a MR is installed in site } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$w_j = \begin{cases} 1 & \text{if a MAP is installed in site } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$y_{jt} = \begin{cases} 1 & \text{if the MR installed in site } j \text{ is active in period } t, \\ 0 & \text{otherwise;} \end{cases}$$

$$r_{jt} = \begin{cases} 1 & \text{if the MAP installed in site } j \text{ is active in period } t, \\ 0 & \text{otherwise;} \end{cases}$$

$$x_{ijt} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to a BS installed in site } j \text{ in period } t, \\ 0 & \text{otherwise;} \end{cases}$$

$$k_{jl} = \begin{cases} 1 & \text{if there is a wireless link between the BSs in sites } j \text{ and } l, \\ 0 & \text{otherwise;} \end{cases}$$

f_{jlt} : Flow between BSs located in sites j and l in time t;

f_{jNt} : Flow between MAP located in site j and Internet (N) in time t.

4.2 The reference model

The first joint network design and management problem for WMNs will be called ($P0$) and it is defined as follows:

The objective function

$$\min \quad \beta \sum_{j \in S} (z_j \gamma_j + p_j w_j) + (1-\beta) \sum_{j \in S} \sum_{t \in T} (\epsilon_j y_{jt} + \psi_j r_{jt}) \Delta(t) \tag{21}$$

The objective function is composed of two terms. The first one represents the installation costs of MRs and MAPs in selected Candidate Sites (Capex), while the second one accounts for the power consumption of the active devices in any time interval (Opex). The parameter β, which varies in the $[0, 1]$ interval, represents the trade-off between the two components, as it changes the importance given to the Opex with respect to the Capex. Starting from $\beta = 1$, when just capital expenses are minimized, we will gradually reach the opposite case of $\beta = 0$ (minimization of power costs only) after evaluating individual values. Then, comparing the intermediate results with the two extreme cases, we will be able to underline the benefits of our approach and show how both network planning and management can be wisely improved by considering them in a joint fashion.

Assignment constraints

$$\sum_{j \in S} x_{ijt} = 1 \qquad \forall i \in I, t \in T \tag{22}$$

$$x_{ijt} \leq a_{ij}(y_{jt} + r_{jt}) \qquad \forall i \in I, j \in S, t \in T \tag{23}$$

Two different assignment constraints are needed. Equations (22) impose that every MC is assigned to one and only one BS. Constraints (23) assign every MC only to a BS that is active and that covers it.

Installation constraints

$$z_j + w_j \leq 1 \qquad \forall j \in S \tag{24}$$

Installation constraints (24) guarantee that at most one device (MR or MAP) is installed in every CS.

Activation constraints

$$y_{jt} \leq z_j \qquad \forall j \in S, t \in T \tag{25}$$

$$r_{jt} \leq w_j \qquad \forall j \in S, t \in T \tag{26}$$

These constraints allow the activation of a MR (25) or a MAP (26) in any time period only if the device has been installed.

Flow conservation constraints

$$\sum_{l \in S} (f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it} x_{ijt} = f_{jNt} \qquad \forall j \in S, t \in T \tag{27}$$

Constraints (27) define the flow balance in site j. The term $\sum_{l \in S} f_{ljt}$ is the total traffic received by j from neighboring sites, $\sum_{l \in S} f_{jlt}$ is the total traffic transmitted by j to neighboring sites, $\sum_{l \in i} d_{it} x_{ijt}$ is the traffic related to the users assigned to j and f_{jNt} is the traffic transmitted to the wired backbone.

Capacity constraints

$$\sum_{i \in I} x_{ijt} d_{it} \leq c_j(y_{jt} + r_{jt}) \qquad \forall j \in S, t \in T \tag{28}$$

$$f_{ljt} + f_{jlt} \leq u_{jl} k_{jl} \qquad \forall j, l \in S, t \in T \tag{29}$$

There are two different groups of capacity constraints. (28) insures that the total traffic demand of the MCs assigned to a BS does not exceed the BS capacity, while constraints (29) refer to the maximum capacity available for existing links.

Link use constraints

$$f_{ljt} + f_{jlt} \leq u_{jl}(y_{jt} + r_{jt}) \qquad \forall j, l \in S, t \in T \tag{30}$$

$$f_{ljt} + f_{jlt} \leq u_{jl}(y_{lt} + r_{lt}) \qquad \forall j, l \in S, t \in T \tag{31}$$

$$f_{jNt} \leq m r_{jt} \qquad \forall j \in S, t \in T \tag{32}$$

Constraints (30) and (31) allow the use of the link (l, j) only in the case BSs in j and l are turned on. Equations (32) state that the capacity of the MAPs Internet access must not exceed m, while forcing the flow toward the backbone to zero if the device in j is not a gateway.

Link existence constraints

$$k_{jl} \leq z_j + w_j \qquad \forall j, l \in S \tag{33}$$

$$k_{jl} \leq z_l + w_l \qquad \forall j, l \in S \tag{34}$$

$$k_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{35}$$

The three constraints above allow the existence of a wireless link between two BSs only if they are both active ((33) and (34)) and neighbors (35).

Best power constraints

$$y_{J_l^{(i)}t} + r_{J_l^{(i)}t} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}t} \leq 1 \qquad \forall i \in I, t \in T, l : 1 ... B_i - 1 \tag{36}$$

Constraints (36) force the assignment of every MC to the most convenient BS, according to a proper parameter such as the received signal strength.

Binary constraints

$$x_{ijt} \in \{0, 1\} \qquad \forall i \in I, j \in S, t \in T \tag{37}$$

$$y_{jt}, r_{jt} \in \{0, 1\} \qquad \forall j \in S, t \in T \tag{38}$$

$$z_j, w_j \in \{0, 1\} \qquad \forall j \in S \tag{39}$$

$$k_{jl} \in \{0, 1\} \qquad \forall j, l \in S \tag{40}$$

Finally, binary constraints impose binary values to some of the decision variables.

4.3 The partial covering-relaxed problem

In order to underline the importance of our study and compare the results in different situations, we have also developed a relaxed variation of the reference model. Just like $(P0)$, the *Partial Covering-Relaxed Problem* $(P1)$ aims at providing a full-coverage network deployment, but in this case our objective is that of guaranteeing network services only to those clients that are active in any time period: in this way, those BSs that have only inactive users in their covering ray can be turned off.

For this purpose, we need to introduce a new binary parameter h_{it} that is equal to 1 if the MC i is providing traffic in time period t. Then, in order to limit the network service only to active users, constraints (22) of $(P0)$ should be replaced by:

$$h_{it} x_{ijt} \leq a_{ij}(y_{jt} + r_{jt}) \qquad \forall i \in I, j \in S, t \in T \tag{41}$$

$(P1)$ can then be written as:

min (21)

s.t. (22), (41), (24) to (40).

5 Resolution approach

The proposed mathematical model has been developed using the AMPL programming language and optimized with the CPLEX solver.

Realistic mesh network instances have been generated modifying the Instance Generator (IG) proposed in [7].

The main features of the IG are given below.

5.1 Instance Generator and input assumptions

Since our model generates a network topology and manages network operation, the main task of the IG is to randomly place CSs and users location in the analyzed area. Also, for each client, the Instance Generator computes two random traffic values in each time interval, according to the different congestion levels presented in Section 3.2. Then, for every pair of MC and CS, it computes the mutual distance and sets the corresponding value of a_{ij} to 1 if user i is in the coverage ray of the BS that could be installed in j. The same operation is done for each couple of CSs, in order to verify if a wireless link is possible between them and set the corresponding parameter b_{jl} to the correct value.

In order to produce factual mesh network instances, some IG input parameters referring to BSs features and derived from real field tests were set to the following values:

- Covering ray for communications between BSs: $450\,m$;
- Covering ray for communications between a BS and a MC: $250\,m$;
- Capacity u_{jl} of the wireless link connecting two BSs located in j and l, $\forall j, l \in S$: $300\,Mbps$;
- Capacity m of MAPs Internet access: $10\,Gbps$;
- Access capacity c_j for a BS located in $j, \forall j \in S$: $40\,Mbps$;
- Installation cost γ_j for a MR located in $j, \forall j \in S$: 200 €;
- Installation cost p_j for a MAP located in $j, \forall j \in S$: 400 €;
- Power consumption ϵ_j for a MR located in $j, \forall j \in S$: $15\,W$;
- Power consumption ψ_j for a MAP located in $j, \forall j \in S$: $18\,W$.

Moreover, specific control parameters are added to the random generation to guarantee the network feasibility.

5.2 Test scenarios

With the help of the IG three different WMN test scenarios were generated. Their features are described in Table 2. The first column reports the name that will be used to identify the instance. The second entry represents the area size (expressed in squared meters) and the next is the number of CSs available in the area. The last column presents the number of users placed in the area.

As introduced in Section 3.2, we considered two different traffic profiles for every test scenario. In both situations, during time period t only a percentage ρ_t of users provides traffic to the network. When the *standard profile* is considered, the traffic value related to each MC is randomly chosen by the IG between 1 and $10\,Mbps$, while the same value ranges from 8 to $10\,Mbps$ in the case of *busy profile*.

Table 2: Characteristics of the WMN test scenarios.

WMN Size	Area Size (m^2)	CSs Number	MCs Number
Small	1000×1000	16	60
Medium	1500×1500	40	130
Large	2500×2500	64	240

5.3 Additional tests and variations

To underline the effectiveness of our results, we introduce three other possible variations of the problem.

Variable capacity for backbone wireless links

As reported in Subsection 5.1, in our tests we use a fixed capacity u_{ij} of 300 $Mbps$ for wireless links connecting two BSs, provided that they are no more than 450 m away. In order to verify the soundness of our assumption, we have also created a set of experience that sets different values of link capacity depending on the BSs mutual distance:

- Distance up to 60 m from BS i to BS j: $u_{ij} = 300Mbps$;
- Distance 60 m – 120 m from BS i to BS j: $u_{ij} = 240Mbps$;
- Distance 120 m – 200 m from BS i to BS j: $u_{ij} = 180Mbps$;
- Distance 200 m – 300 m from BS i to BS j: $u_{ij} = 120Mbps$;
- Distance 300 m – 450 m from BS i to BS j: $u_{ij} = 60Mbps$.

Thus, our purpose is to demonstrate that no substantial variation in Capex and Opex values, as well as in the network design and management, appears when the fixed capacity assumption is adopted.

The cellular comparison

Here we assume that no router can be installed so that each CS can host only a gateway (MAP). This case represents a *cellular network* where every Base Station behaves as a gateway, being directly connected to the backbone and routing the traffic towards the Internet without the help of other nodes. This *MAPs only* scenario aims at sizing the energy savings that can be obtained if a multi-hop mesh network is deployed instead of a cellular one.

The two-step approach

In the third test, the energy management model proposed in [7] and reported in Section 3.3.2 is applied to a pre-computed network design. Differently from the network planning considered in [7], this is directly obtained from the model we propose by setting the weight parameter β to 1, so it is optimized to get the minimum capital expenses. This kind of approach can be identified as a *two-step* approach, since the network design is computed first and only then an energy management model can be applied to the network. Thus, by comparing our joint model results with the ones given by the *two-step* optimization, we strive to show the effects of a combined approach on the network deployment and the benefits on energy savings.

The relaxed two-step approach

Finally, we test a different version of the *two-step* procedure described above where the energy management is executed by considering only the active MCs. In this last case, the model presented in Section 3.3.2 is modified by excluding constraints (14) and setting the value of the summation in constraints (13) equal to h_{it}. We refer to [7] for more details on the adopted relaxing technique. This *relaxed two-step* approach will be compared with the results obtained by our problem $(P1)$.

6 Numerical results

In this section, we present selected results from a large set of instances for Problems $(P0)$, $(P1)$ and its variations.

6.1 Savings obtained using reference model $(P0)$

This subsection is devoted to the presentation of summary results as well as more detailed results concerning the application of the basic planning and operation problem $(P0)$.

6.1.1 Summary results

For every scenario, we tested different values of β to see the effect of giving more weight to the operational and energetic aspect of the network.

Table 3 provides an overview of the percentage of energy savings that can be obtained by exploiting the joint design and management model ($P0$). Each entry refers to a particular value of β applied to the previously described test scenarios. The percentages are calculated with respect to the energy requirement of the same test scenarios when β is set to 1. In fact, when $\beta = 1$ no energy saving operational considerations are taken into account and the model provides a simple network design optimization. As a result, all the installed BSs are constantly turned on and no energy management mechanism is enabled.

One can observe from the values in the table that by just setting β to 0.8, which enables the energy management term of the objective function, the energy consumption during the day decreases by more than 30% in the best situations. These reductions are due to the fact that, when the weight parameter is smaller than 1, our joint approach is pushed to optimize not only the topology but also the operation of the considered network. Therefore, only those BSs that are required for routing the MCs' traffic or guaranteeing the total area coverage are turned on, while the others can be powered off. Further decreases of β lead to low decreases of the energy consumption in the "busy" version of all the test scenarios, while better results come from the cases with standard traffic. This difference in the network behavior is clearly caused by a higher amount of traffic that has to be managed in the "busy" profile cases.

6.1.2 Detailed results

Some detailed results on energy efficiency, costs and energy management can be found in Table 4, that shows more clearly how ($P0$) behaves when applied to the largest test scenario. The rows of the table display, respectively, the values of capital expenditures (Capex, expressed in Euro), the energy requirements during the day (expressed in Watt hour), the daily energy expenses (expressed in Euro and based on the Italian energy cost for business users of 0.2 €/hour) and the number of installed routers (MRs) and gateways

Table 3: Comparison of energy saving percentages obtained from ($P0$) in all test scenarios (percentages are referred to the cases of $\beta = 1$).

	Small		Medium		Large	
	Standard	Busy	Standard	Busy	Standard	Busy
$\beta = 0.8$	20.49%	29.32%	12.39%	32.11%	17.94%	25.51%
$\beta = 0.5$	27.66%	29.32%	14.98%	32.11%	20.80%	28.01%
$\beta = 0.1$	28.69%	30.09%	20.87%	32.67%	23.11%	28.84%

Table 4: Size "large", Traffic "standard". Summary of the results from ($P0$) with different values of β and comparison with *two-step* approach.

		$\beta = 1$	**2-step**	$\beta = 0.5$	$\beta = 0.1$
Capex (€)		9600	9600	10000	12400
Energy (Wh/day)		16704	15264 ***(-8.62%)***	13230 *(-20.80%)*	12843 ***(-23.11%)***
Running Exp. (€/day)		3.34	3.05	2.65	2.57
Installed MRs		44	44	46	50
Installed MAPs		2	2	2	6
On MRs – MAPs	t_1	44 - 2	40 - 2	31 - 2	28 - 4
	t_2	44 - 2	39 - 2	31 - 2	29 - 3
	t_3	44 - 2	40 - 2	33 - 2	30 - 5
	t_4	44 - 2	43 - 2	44 - 1	39 - 4
	t_5	44 - 2	39 - 2	34 - 2	30 - 4
	t_6	44 - 2	41 - 2	39 - 2	35 - 4
	t_7	44 - 2	39 - 2	32 - 2	28 - 4
	t_8	44 - 2	39 - 2	32 - 2	28 - 4

(MAPs). The percentages in parenthesis show the savings with respect to the case with $\beta = 1$. Every column, except for the second one (that will be explained in the next subsection), gathers the results obtained with different values of β. One can see how the energy savings increase as β decreases, how the planning is different (different number of installed MRs and MAPs) and how the operation changes.

The same trend can be observed in Figure 1 where the scenario was chosen since it was the easiest to appreciate from the visual point of view. Every subfigure represents the network configuration obtained with a certain value of β and shows its behavior in a given time period. In particular, the lowest- and the highest-traffic time intervals (t_2 and t_4) are analyzed. Black triangles and squares symbolize active MRs and MAPs respectively, while MRs and MAPs that are installed but inactive are represented by the same white symbols. All the MCs are depicted as black dots, but only the MCs providing traffic are connected by dotted lines to the BS they are assigned to. However, since $(P0)$ guarantees the total network coverage, every MC resides at least in one BS coverage area, represented in the pictures by a dotted circumference centered in each active BS location. Finally, the network structure is revealed by black lines linking MRs and MAPs for routing the traffic received from the clients towards the Internet.

If $\beta = 1$, only Capex costs are minimized (Figures 1a and 1b), no energy management is enabled and all the installed BSs are active during the whole day. Even when only 6 MCs are active (t_2), so much as 11 MRs are turned on: they are useful for providing the network coverage but, on the other hand, the great overlap between the coverage areas would allow to turn off some of them. This is what happens when $\beta < 0$. As an example, in Figures 1c and 1d the solution obtained for $\beta = 0.5$ is displayed. Now, only those MRs that are really required for serving active MCs or providing network coverage are turned on (7 in time period 2, 10 in time period 4). Therefore, thanks to the role played by the power management mechanism, energy savings of 21.5% with respect to the previous case can be reached for the analyzed scenario. Also note that when the value of β decreases, the network design changes in order to find the best trade-off between Capex and Opex savings.

6.1.3 Comparison with the case of variable backbone links capacity

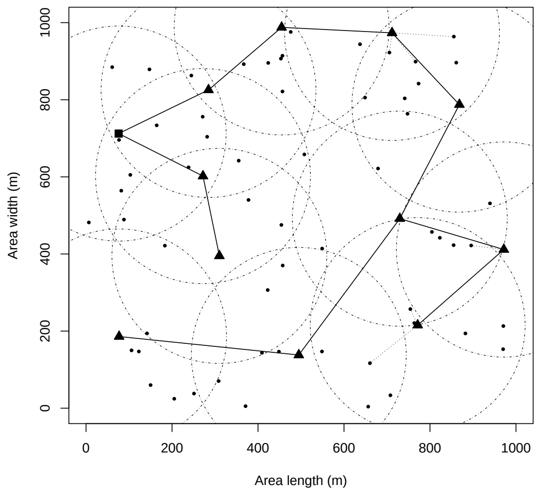
Figure 2 presents some network configurations obtained by letting the backbone links capacity vary with the distance between the BSs. Given that the displayed test scenario, the values of β and the selected time periods are the same of Figure 1, one can easily compare the pictures in order to focus on the differences caused by the capacity variation..

Looking at the cases of $\beta = 1$ we note that, in both Figure 1 (fixed link capacty) and Figure 2 (variable link capacity), 11 MRs and 1 MAP are constantly turned on, which indicates that Capex and Opex costs are the same. Now, even though Opex expenditures do not vary in Figure 2b (representing the highest-traffic time period) more backbone links are activated due to their reduced capacity.

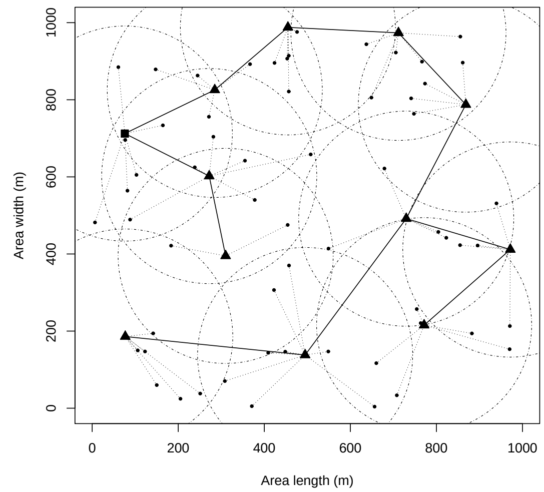
Another difference is shown in Figures 2c and 2d, representing the network configurations when $\beta = 0.5$. We observe that in the variable capacity case one more MAP is deployed and switched on in place of a MR, allowing the traffic to be routed through two different access points. This way, a lower number of links and particularly routers has to be installed: 10 MRs and 2 MAPs compared to 12 MRs and 1 MAP installed in the original example. Accordingly, we observe a slight increase (+3.68%) in Opex due to the MAPs higher operational cost, while no additional Capex expenses are required.

6.1.4 Comparison with the 2-step procedure

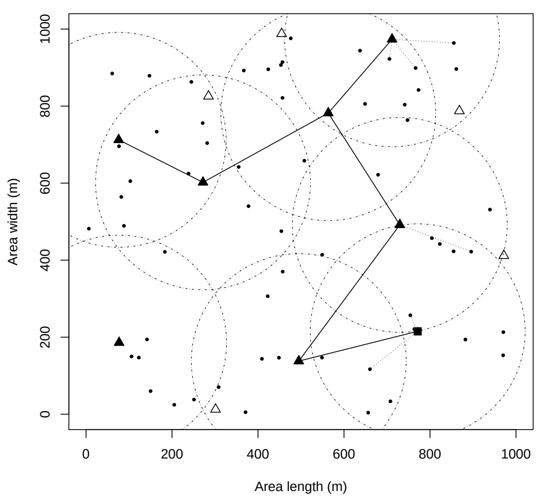
An important point that we wanted to evaluate is what is the level of savings provided by the joint optimization when compared with the optimal energy operation of a well designed network. To be fair, we optimized first the planning by using $(P0)$ with $\beta = 1$, and next we introduced the resulting network into an optimal operation model, such as the one given in [7]. The results are provided in the tables in the column titled "2-step". Note that in this case, since the two optimization problems are independent, it is not possible to adjust the importance of the energy issue with respect to the installation cost according to particular network needs. Such a regulation can be done exclusively by applying the joint design and management approach,



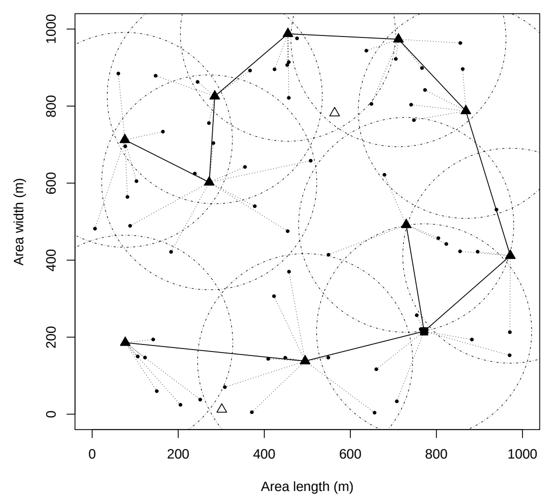
(a) $\beta = 1$, t_2: *11 MRs, 1 MAP.*



(b) $\beta = 1$, t_4: *11 MRs, 1 MAP.*



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



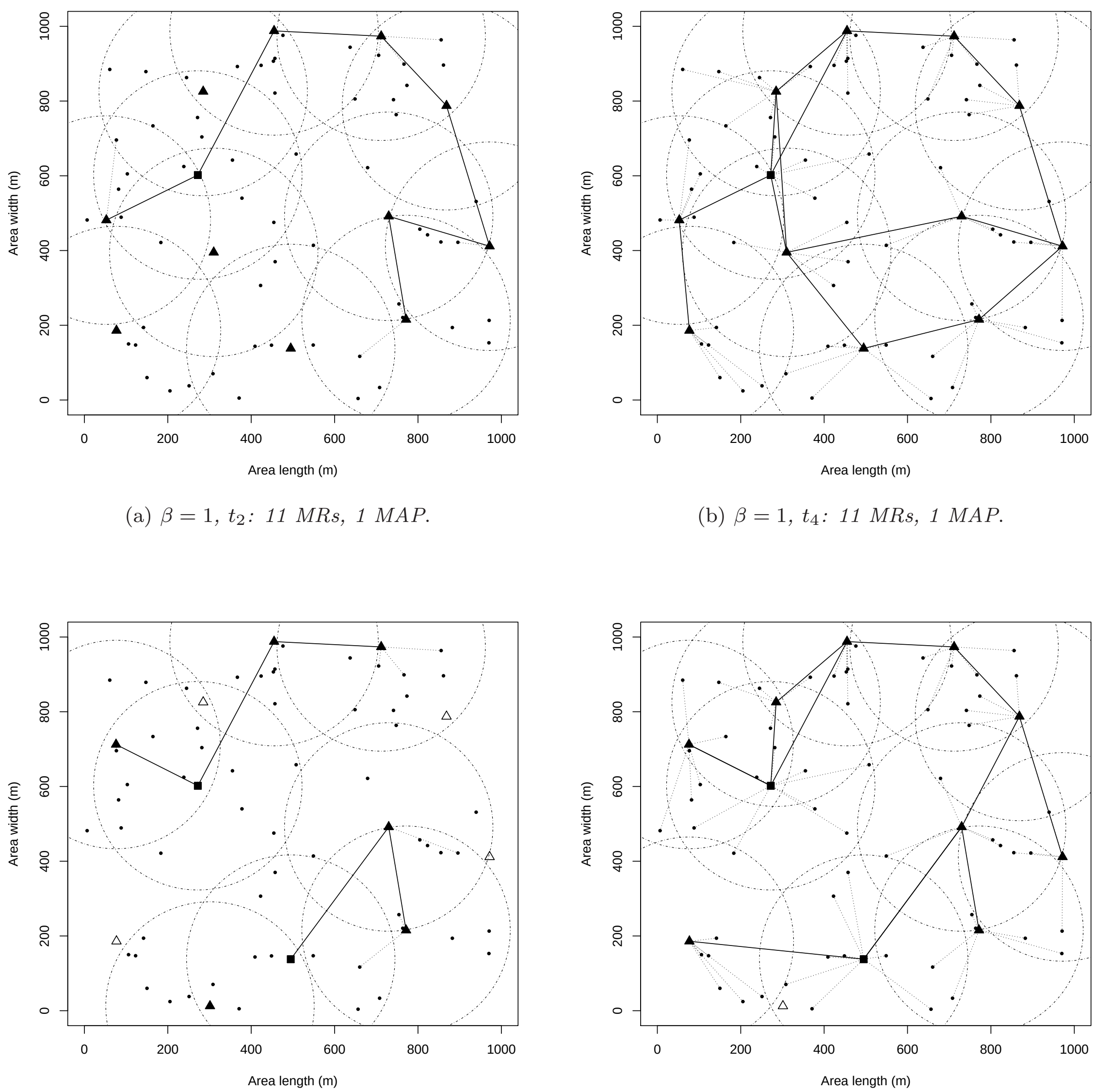
(d) $\beta = 0.5$, t_4: *10 MRs, 1 MAP.*

Figure 1: ($P0$): “Small” scenario, “Standard” traffic. Network design and behavior for different values of β.

where the network planning and management are handled at the same time and tuned by a proper weight parameter.

Observing first the numbers obtained for $\beta = 1$ and then the ones corresponding to lower values of β, it is clear that by enabling the power management mechanism good energy saving can be achieved. In particular, our joint approach produces savings that are not limited to the minimum cost topology, but it trades off between the two terms of the objective function to reach the best compromise of energy saving and installation cost reduction. For example, if $\beta = 0.5$ we more than double the energy savings given by the *two-step* approach at the cost of a modest increase (+4.17%) in Capex expenses. Similarly, by investing the 29.17% more in the installation phase, energy savings of almost 24% are possible for $\beta = 0.1$.

It must be noticed that, despite the fact that Capex increases could seem higher than energy savings, the latter spread during the whole period of operation, while network operators meet capital investments only once. Taking the case of $\beta = 0.5$ as an example, one can estimate that the additional initial investments,



(a) $\beta = 1$, t_2: *11 MRs, 1 MAP.*

(b) $\beta = 1$, t_4: *11 MRs, 1 MAP.*

(c) $\beta = 0.5$, t_2: *6 MRs, 2 MAP.*

(d) $\beta = 0.5$, t_4: *9 MRs, 2 MAP.*

Figure 2: ($P0$): "Small" scenario, "Standard" traffic, variable backbone links capacity. Network design and behavior for different values of β.

corresponding to 400 €, can be recovered from the energy saving in less than two years of network operation (259.15 €/year spared), which is a short period compared to the average network life.

6.1.5 Cellular comparison

In Table 5 the same "large" scenario is considered, but in this case the *MAPs only* approach is applied. Such an approach "mimics" the case of a purely cellular network. Thus, the idea of this comparison is to determine the levels of energy savings provided by the flexibility of Mesh Networks. Back to Table 5, we present in bold the percentage increases in Capex and energy expenditures with respect to the values in Table 4. Clearly, since only the most expensive and energy hungry devices can be deployed and that there is no flexibility related to Mesh networking, both capital investments and power expenditures face a sensible

Table 5: Size "large", Traffic "standard", *MAPs only* approach. Summary of the results with different values of β.

		$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
Capex (€)		18000	18800	21600
Capex Diff. – vs ($P0$)		**+87.50%**	**+88.00%**	**+74.19%**
Energy (Wh/day)		19440	15876 *(-18.33%)*	15120 *(-22.22%)*
Energy Diff – vs ($P0$)		**+16.38%**	**+20.00%**	**+17.73%**
Running Exp. (€/day)		3.89	3.18	3.02
Installed MAPs		45	47	54
On MRs – MAPs	t_1	45	34	33
	t_2	45	33	31
	t_3	45	36	35
	t_4	45	44	44
	t_5	45	37	34
	t_6	45	41	39
	t_7	45	34	32
	t_8	45	35	32

increase. Despite that, our joint approach applied to the cellular case still insures energy savings of 18% for $\beta = 0.5$ with 4.44% extra Capex and more than 22% for $\beta = 0.1$.

6.2 Savings obtained using the partial covering-relaxed model ($P1$)

Tables 6 and 7 show the results computed for the smallest scenario with respectively standard and busy traffic profile for the partial covering-relaxed problem ($P1$). The tables show capital expenditures, the amount of energy and its cost in a day and the number of installed gateways and routers. Moreover, energy decrease percentages obtained by comparing the results with the ones of ($P0$) for the same scenario are reported. The column "relax 2-step" refers to the last model variation described in Section 5.3 which, starting from a given complete coverage topology, manages the network so as to provide services only to the active users. In this case, the energy decrease percentage is related to the value of energy found by the *two-step* approach rather than the one of ($P0$). Also, in order to illustrate the behavior of the energy management mechanism we also report the number of MRs and MAPs switched on in every time interval.

As already noticed, by jointly optimizing installation and operation costs we can obtain high energy savings. Significant is the case of $\beta = 0.5$: if one more MR is installed at the modest extra cost of 200 €, power consumption will be reduced by almost 22%. Formulation ($P1$) shows the same behavior of ($P0$) but,

Table 6: Size "small", Traffic "standard". Summary of the results from ($P1$) with different values of β and comparison with *relaxed two-step* approach.

		$\beta = 1$	**relax 2-step**	$\beta = 0.5$	$\beta = 0.1$
Capex (€)		2600	2600	2800	3400
Energy (Wh/day)		3762	3267 ***(-15.18%)***	2952 *(-21.53%)*	2727 ***(-27.51%)***
Running Exp. (€/day)		0.75	0.65	0.59	0.55
Energy Diff. – vs ($P0$)		-14.34%	-6.44% (vs *2-step*)	-7.08%	-12.93%
Installed MRs – MAPs		11 - 1	11 - 1	12 - 1	11 - 3
On MRs – MAPs	t_1	9 - 1	7 - 1	6 - 1	4 - 2
	t_2	5 - 1	5 - 1	4 - 1	0 - 3
	t_3	10 - 1	8 - 1	6 - 1	4 - 2
	t_4	11 - 1	10 - 1	10 - 1	8 - 3
	t_5	10 - 1	9 - 1	7 - 1	7 - 1
	t_6	10 - 1	9 - 1	9 - 1	5 - 3
	t_7	10 - 1	8 - 1	7 - 1	6 - 2
	t_8	9 - 1	7 - 1	7 - 1	5 - 2

Table 7: Size "small", Traffic "busy". Summary of the results from $(P1)$ with different values of β and comparison with *relaxed two-step* approach.

		$\beta = 1$	**relax 2-step**	$\beta = 0.5$	$\beta = 0.1$
Capex (€)		3400	3400	3400	3600
Energy (Wh/day)		4572	3717 ***(-18.70%)***	3672 *(-19.69%)*	3654 ***(-20.087%)***
Running Exp. (€/day)		0.91	0.74	0.73	0.73
Energy Diff. – vs $(P0)$		-21.60%	-9.83% (vs *2-step*)	-10.92%	-10.38%
Installed MRs – MAPs		15 - 1	15 - 1	15 - 1	14 - 2
On MRs – MAPs	t_1	8 - 1	6 - 1	6 - 1	6 - 1
	t_2	10 - 1	2 - 1	2 - 1	0 - 2
	t_3	10 - 1	7 - 1	7 - 1	7 - 1
	t_4	15 - 1	15 - 1	15 - 1	14 - 2
	t_5	13 - 1	13 - 1	12 - 1	12 - 1
	t_6	14 - 1	13 - 1	13 - 1	12 - 2
	t_7	12 - 1	9 - 1	9 - 1	9 - 1
	t_8	10 - 1	8 - 1	8 - 1	8 - 1

compared to the latter, $(P1)$ can reduce the energy expenditures of a percentage in the 9% to 15% range. This appears straightforward, since the network service must be guaranteed only for the users providing traffic, while BSs covering only idle users can be powered off. Looking now at the last part of the table, one can notice how the network devices are managed in order to minimize the total power consumption. During lower-traffic periods (intervals 1 and 2), 9 or 5 MRs over 11 are turned on when $\beta = 1$: the management mechanism is not able to power off other BSs due to the small covering ray of wireless mesh devices. On the other hand, the highest number or routers is used when the traffic presents its peak. Decreasing the value of β and focusing in particular on $\beta = 0.1$, we observe a smaller number of active BSs in all time intervals (even 0 routers in period 2), while a higher number of MAPs is installed and turned on in order to better manage the traffic of the MCs. The results described above are represented in Figure 3. On the left side, the solutions obtained for $\beta = 1$, 0.5 and 0.1 in time period 2 are displayed, while solutions for time period 4 are on the rigth side.

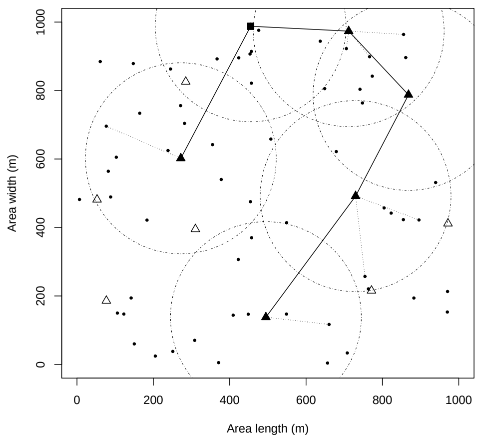
For the sake of completeness, we report in Table 7 the results we found for the "small" scenario where active users provide an amount of traffic between 8 and 10 $Mbps$, what we call the "busy" scenario. Compared to the ones in Table 6, the power savings are lower as was expected given that we get less flexibility when there is more demand. Nevertheless the approach still manages to get percentage of savings around 20% for both $\beta = 0.5$ and $\beta = 0.1$.

Finally, in Figure 4 we summarize the percentage variations of capital and energy expenses obtained by applying $(P0)$ (Figure 4a) and $(P1)$ (Figure 4b) to the three "standard" traffic test scenarios. Each point in the graphs corresponds to the percentage increment of Capex and decrement of energy costs, with respect to the case of $\beta = 1$, obtained by playing with the weight parameter.

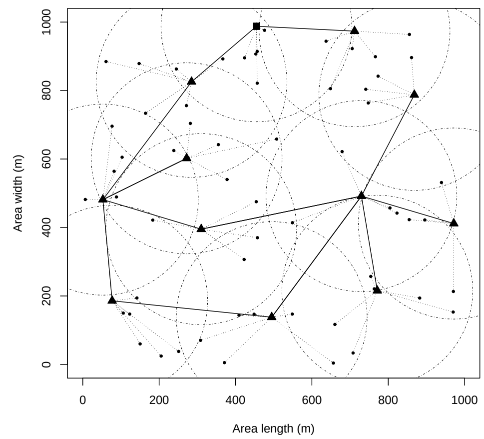
7 Conclusion

In this paper we have tackled the problem of designing energy-aware Wireless Mesh Networks. Starting from the key idea that a wise network management is probably the best way to save power and reduce operational expenses, we have developed an optimization framework that selects the devices to be installed and jointly considers their dynamic energy-aware operation. Therefore, the objective of this optimization approach is that of minimizing at the same time capital and operational expenses, which are mostly due to energy consumption.

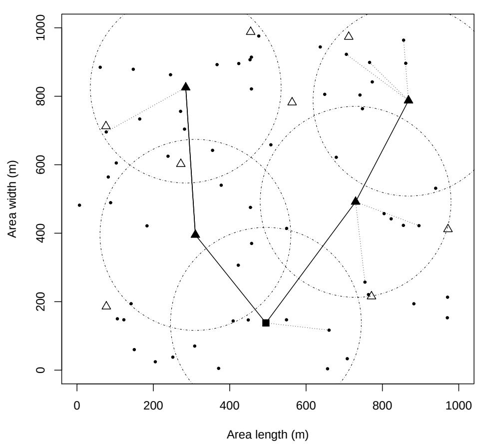
By mean of three test scenarios and several additional model variations, we have shown that an optimal network topology from the installation cost point of view does not produce a network that is optimal for an energy-aware operation and that it is necessary to plan ahead with the use of the joint planning and operational tool. In particular, varying the trade-off parameter β between Capex and Opex, we have found



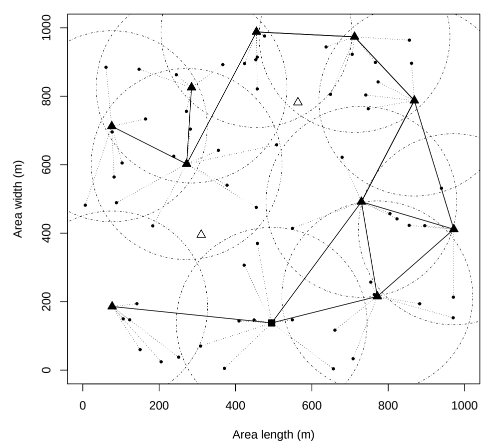
(a) $\beta = 1$, t_2: *5 MRs, 1 MAP.*



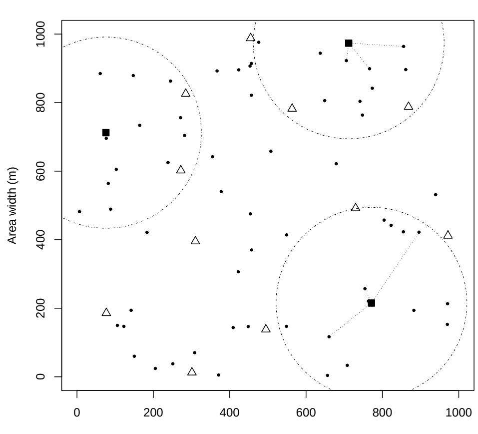
(b) $\beta = 1$, t_4: *11 MRs, 1 MAP.*



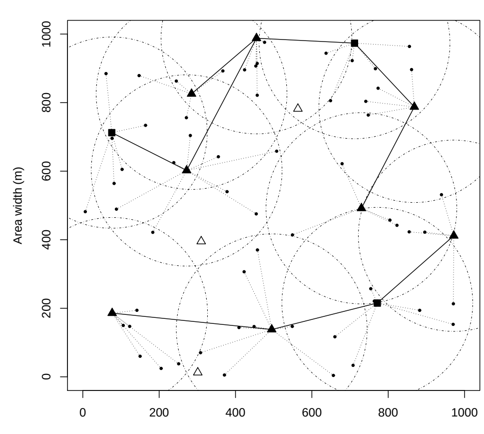
(c) $\beta = 0.5$, t_2: *4 MRs, 1 MAP.*



(d) $\beta = 0.5$, t_4: *10 MRs, 1 MAP.*

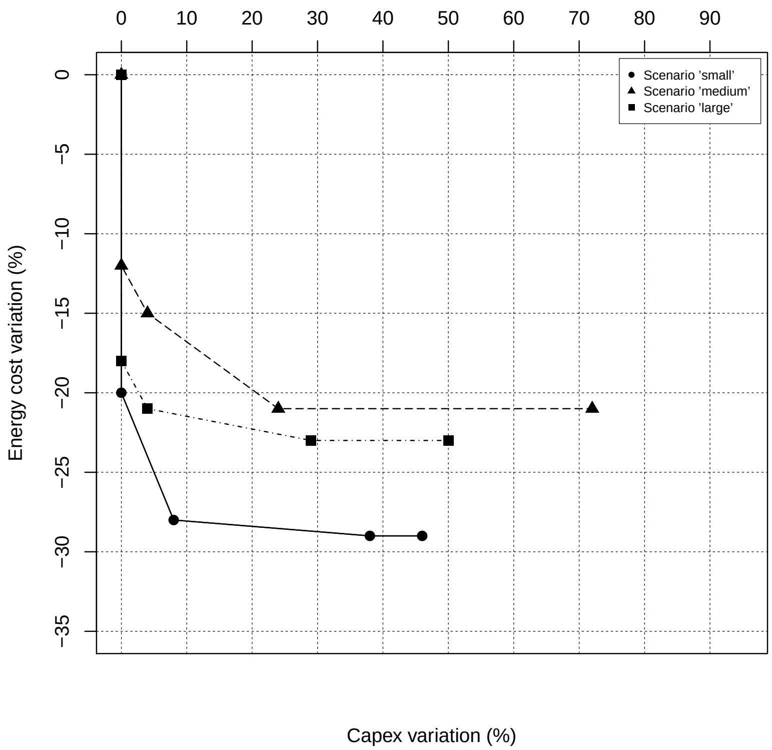


(e) $\beta = 0.1$, t_2: *0 MRs, 3 MAPs.*

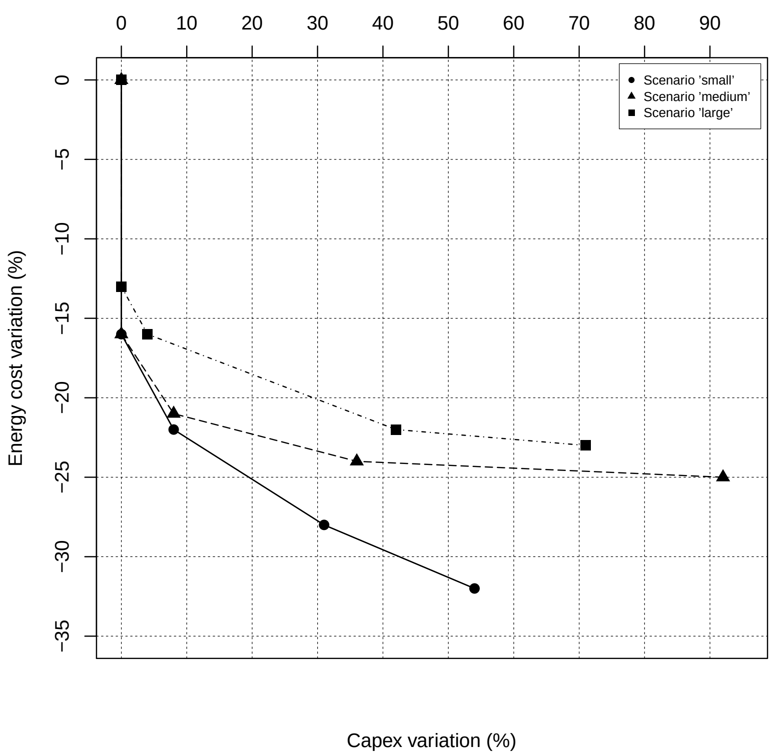


(f) $\beta = 0.1$, t_4: *8 MRs, 3 MAPs.*

Figure 3: ($P1$), “Small” scenario, “Standard” traffic. Network design and behavior for different values of β.



(a) $(P0)$, *"standard" traffic.*



(b) $(P1)$, *"standard" traffic.*

Figure 4: Capital and energy expenses variations for different values of β.

that important energy savings can be reached at the cost of little increases in installation investments. Moreover, the effectiveness of our framework has been confirmed by comparing our results with the ones obtained from a more "traditional" two-step approach, where network planning and energy-aware operation are optimized separately. The joint framework was also applied to a cellular architecture, showing that it still produces good energy savings results but that they are less important than those obtained with mesh networking. Finally, we evaluated the effect of partial covering in the procedure and found that more than ten percent energy savings can still be achieved when some coverage constraints are relaxed, regardless of the case, which shows the importance of a more flexible wireless network coverage control for energy savings.

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