Energy Savings in Wireless Mesh Networks in a Time-Variable Context

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Published on: 01 Apr 2012 - Mobile Networks and Applications (Springer US)

Topics: Wireless mesh network, Wireless network, Energy consumption, Municipal wireless network and Energy management

Noname manuscript No.
(will be inserted by the editor)

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Abstract Energy consumption of communication systems is becoming a fundamental issue and, among all the sectors, wireless access networks are largely responsible for the increase in consumption. In addition to the access segment, wireless technologies are also gaining popularity for the backhaul infrastructure of cellular systems mainly due to their cost and easy deployment. In this context, Wireless Mesh Networks (WMN) are commonly considered the most suitable architecture because of their versatility that allows flexible configurations. In this paper we combine the flexibility of WMN with the need for energy consumption reduction by presenting an optimization framework for network management that takes into account the trade off between the network energy needs and the daily variations of the demand. A resolution approach and a thorough discussion on the details related to WMN energy management are also presented.

1 Introduction

Green Networking consists of a rethinking of the way networks are built and operated so that not only costs and performance are taken into account but also their energy consumption and carbon footprint. It is quickly becoming one of the major principles in the world of networking, given the exponential grow of Internet traffic that is pushing huge investments around the world for increasing communication infrastructures in the coming years. In fact, the Information and Communication Technology (ICT) sector is said to be responsible for 2% to 2.5 % of the **GHG** annual emission [1, 2,3] as it generates around $0.53Gt$ (billion tonnes) of *carbon dioxide equivalent* (CO_2e). This amount is expected to increase to $1.43GtCO_2e$ in 2020 (data from [4]).

Among Internet related networking equipment, it is the access the one with the major impact in energy expenditures. It has been estimated that access networks consume around 70 % of overall telecommunications network energy expenditures and this percentage is expected to grow in the next decade [5,6]. An important part of the energy consumption is given by the wireless part of the access and it has been estimated that the base stations represent 80% of the total wireless consumption [7]. It follows that being able to minimize base station consumption represents an important green networking objective.

An increasingly popular type of wireless access are the so-called Wireless Mesh Networks (**WMN**s) [8] that provide wireless connectivity through much cheaper and more flexible backhaul infrastructure compared with wired solutions. The nodes of these dynamically self-organized and self-configured networks create a changing topology and keep a mesh connectivity to offer Internet access to the users. Obviously, the use of wireless technologies also for backhauling can potentially make the issue of energy performance even more severe if appropriate energy saving strategies are not adopted.

As a matter of fact, the resources of Wireless Access Networks are, for long periods of time, underemployed, since only a few percentage of the installed capacity of the Base Stations (**BS**) is effectively used and this results in high energy waste [9,10]. In **WMN**s also, network devices are active both in busy hours and in idle periods. This means that the energetic consumption does not decrease when the traffic is low and that it would be possible to save large amounts of energy just by switching off unnecessary network elements.

The focus of our work is to combine the versatility of Wireless Mesh Networks with the need of optimizing energy consumption by getting advantage of the low demand periods and the dynamic reconfigurations that are possible in WMNs. We propose to minimize the energy in a time varying context by selecting dynamically a subset of mesh **BS**s to switch on considering coverage issues of the service area, traffic routing, as well as capacity limitations both on the access segment and the wireless backhaul links. To reach our objective, we provide an optimization framework based on mathematical programming that considers traffic demands for a set of time intervals and manages the energy consumption of the network with the goal of making it proportional to the load.

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Energy management in wireless access networks have been considered very recently in a few previous works [11, 9, 12, 2, 13, 14, 15, 1] (see Section 2 for a detailed review of the state of the art). In this paper, we present a novel approach for the dynamic energy management of WMNs that provides several novel contributions:

- We consider not only the access segment but also the wireless backhaul of wireless access networks;
- We combine together the issue of wireless coverage, for the access segment, and the routing, for the backhaul network, and optimize them jointly;
- We explicitly include traffic variations over a set of time intervals and show how it is possible to have energy consumption following these variations;
- We provide a rigorous mathematical modeling of the energy minimization problem based on Mixed Integer Linear Programming (MILP), and solve it to the optimum.

The paper has been structured as follows. After a brief survey of the literature concerning general and wireless Green Networking in **ICT** in Section 2 we present the system model and preliminary descriptions in Section 3. The optimized modeling approach for system management is introduced in Section4. The resolution approach and a thorough results analysis are presented in Section 5. Section 6 concludes the paper.

2 Related work

The problem of energy consumption of communication networks and the main technical challenges to reduce it have been presented in the seminal work by Gupta and Singh [16]. Several proposals to reduce networks foot print as well as energy consumption have appeared in the last few years, considering both wireless and wired networks [17, 18, 19, 20, 21, 22, 23, 24].

Good overviews of the research on green networking and methodological classifications are given in [25, 26] where different methods adopted in the literature for both wired and wireless networks are surveyed.

In what follows, we focus on wireless networks only.

The literature in wireless device energy optimization is quite large, given the limitation of the battery and the natural restrictions of the wireless medium. In fact, energy consumption has always been a concern for wireless engineering given the mobility of users that require portability, which makes coverage and battery life issues a true challenge. There is, indeed, a large body of work on energy-efficiency for *devices* and *protocols* for cellular, WLAN and cellular systems (see [27], for an excellent survey). However, the interest for energy optimization of the wireless infrastructure has only picked up in recent years given the explosion in Internet wireless applications.

There has been some work to compare wireless and wireline infrastructure consumption. For instance, let us mention [16] where the energy cost ($Wh/Byte$) for a transmission over the Internet was compared to the cost of the same transmission in a wireless context (for instance *Wi-Fi 802.11b*). Wireless resulted more efficient by a small factor with omnidirectional antenna and it was found that the factor could be improved using directive antennas.

Our main concern, however, is wireless network management for which we have found articles that deal either with Wireless Local Area Networks (WLANs) or with traditional cellular access networks.

In WLANs, we mention the work of [11] that presented strategies based on the resource on-demand (RoD) concept. [9] proposed an analytical model to assess the effectiveness of RoD strategies and [12] shows management strategies for energy savings in solar powered 802.11 wireless MESH networks.

Concerning cellular access networks, [2] considered the possibility of switching off some nodes but without considering traffic variations, which can produce substantial savings given that cellular systems are generally dimensioned for peak traffic conditions. [14], on the other hand, studied deterministic traffic variations to characterize energy savings and showed that they can be around 25 - 30% for different types of regular cell topologies. Another energy management study is provided by [13] where it is shown that the on-off strategy for UMTS BS is feasible in urban areas. [15] considered a random traffic distribution and dynamically minimized the number of active **BS**s to meet the traffic variations in both space and time and [1] presented an optimization approach for dynamically managing the energy consumption.

The differences of our work with the papers mentioned above is that the later deal exclusively with access networks while our goal is to manage the energy consumption of WMNs that use the wireless medium not only for the access segment but also for the backbone. The presence of the wireless backbone forces us to consider the routing of traffic from base stations (or mesh access points) to the mesh gateways (interconnecting the WMN to the wired network). This issue, in addition to the coverage aspects of the service area typical of the access segment, makes the problem of energy management in WMNs a combination of the problems considered so far for wired and wireless networks. To the best of our knowledge, this is the first paper proposing a network management framework aimed at optimizing the energy consumption of WMNs.

3 System model and problem description

In this Section, we first present the physical and technological features of the system. Next, we describe the details of the traffic scenarios that will be essential to understanding the modeling issues. Finally we present the model that will be used as the basis for the energy efficient formulation and introduce the general approach to WMN energy management.

3.1 Description of the system

The WMN architecture such as the one presented in Figure 1 is made up of fixed and mobile elements, namely Mesh

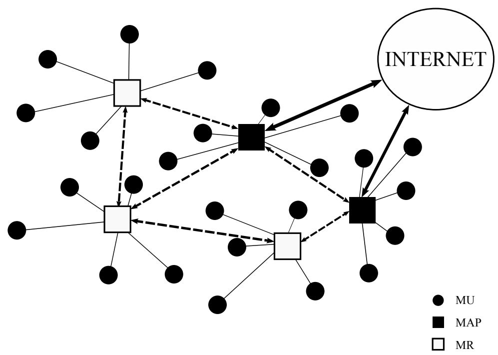

Figure 1: Architecture of the network analysed

Routers (**MR**) and Mesh Users (**MU**). **MR**s could have different functions and features building up a variety of structures and architectures. A restricted part of the set of routers is used as gateway to other larger networks, typically the Internet. In particular, the so called Mesh Access Points (**MAP**) can communicate with the other routers with a radio communication channel and also have a fixed connection to the Internet. In what follows, the term Base Station (**BS**) will be used as a general term to design either **MAP**s or **MR**s. In our networks' *distribution system* **MR**s and **MAP**s communicate through a dedicated wireless channel, each **MU** is connected to the nearest active base station and, through multi hop communications, to the Internet.

The devices are all equipped with multiple network interfaces, so we can infer that the traffic in a given link does not affect closer links. The interference is not totally removed but it can be minimized installing directive antennas and adopting a smart frequency assignment algorithm as suggested in [28]. So every link between two base stations has a fixed bidirectional capacity. We also assume that this capacity does not depend on the distance and that a wireless link is possible between two **MR**s only if they have a distance to each other lower than a value called *covering ray*.

Even if the modeling approach proposed is general and can be used with any wireless technology, we have focused our analysis on WiFi WMNs. The technology used among routing devices is assumed to be Wi-Fi 802.11/n with a nominal capacity of 450 Mbps and a covering ray of 450 metres. Concerning the communication between users and BSs, we suppose that the access technology is Wi-Fi 802.11/g with 54 Mbps. This access capacity has to be shared among all the **MU**s assigned to a given **BS**. A **MU** can be assigned to a **MR** if and only if it is inside a circular cell with the center at the **BS** and a ray of 250 metres. Note that the difference between the two mentioned rays is due to the use of directive antennas which allow to double the covering distance.

Also assumed is a certain percentage of losses derived from the protocol **OH** that reduce the effective link capacities. The details on this issue will be given in subsection 5.2.

index t	**Starting**	**ending**	**duration (h)**	p_t
1	0	3	3	0.35
2	3	6	3	0.1
3	6	9	3	0.45
4	9	12	3	1
5	12	15	3	0.7
6	15	18	3	0.85
7	18	21	3	0.6
8	21	24	3	0.5

Table 1: Day division in time intervals and related level of congestion

3.2 Traffic profiles

In [29] and [30] the characteristics of the traffic in Wireless Access Networks have been analyzed and it is shown how the traffic during the day can be split into intervals of equal length that we define ΔT. Since we want to optimize the energy consumption during the day in such a way as to make the consumption $f$ollow the demand as much as possible, it is important to assume a realistic traffic profile. For that, we have divided the day into eight intervals of three hours and have assigned a probability p_t of test points requesting demand in each interval t that follows the traffic characteristics presented in [30] and [29]. The results are presented in Table 1.

Moreover we used two different traffic profiles:

- *standard*, with traffic randomly generated in the interval from 1 to 10 Mbps
- *busy*, with a traffic request that varies between 8 and 10 Mbps.

3.3 A general approach to WMN energy management

The general problem we are considering aims at managing network devices in order to save energy when some of the network resources, namely BSs and the links connecting them, are not necessary and can be switched off. Even if the specific implementation issues are out of the scope of this work, it is easy to see that an energy management strategy like the one we propose can be integrated with no difficulty in the network management platforms that are commonly adopted for carrier grade WMNs and that allow the centralized and remote control of all devices and the change of their configuration with relatively slow dynamics (hours) [31].

From an energy efficiency standpoint, there are several questions that should be answered concerning the deployment and operation of WMN. It is clear that in order to follow the varying demand, it is not enough to consider that some mesh BSs should be powered down. To have an effective energy management system, we must address the question of which base stations to select, how to guarantee that the requested QoS is maintained despite shutting down the equipment, how users are reassigned after shut down and how the initial coverage and network topology has an impact on energy savings and energy consumption.

Given that an appropriate network planning provides the basis for an effective energy management operation, we now present the basic planning model introduced in [32] and explain how that model is modified to obtain a general framework for energy management.

The idea of the model is that, given a set of TP (Test Points) representing aggregated points of demand and a set of possible BS sites decide where and what type of equipment to locate while satisfying the TP demand and minimizing costs. In more formal terms, let S be the set of the candidate sites (CS) to install routing devices like **MR**s or **MAP**s, I the set of test points and N a special node representing the Internet.

The network topology is defined by two binary parameters: a_{ij} that is equal to 1 if a **BS** in **CS** j covers the **TP** i and b_{jl} equal to 1 if **CS** j and in **CS** l could communicate through a wireless link. The traffic requested by **TP** i is denoted by d_i.

Binary variables x_{ij} are used for the assignment of **TP** i to **CS** j, while z_j are installation variables related to **CS**j. Additional binary variables are w_{jN}, that show if a **MAP** is installed in **CS** j, and y_{jl} that define if there is a wireless link between the two **CS**s j and l.

The integer variable f_{jl} represents the traffic flow on wireless link (j,l) while f_{jN} is the flow from the **MAP** in **CS** j to the Internet.

Given the above parameters and variables we can summarize the mathematical formulation as follows:

$$\min \sum_{j \in S} (c_j z_{jt} + p_j w_{jN}) \tag{1}$$

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

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

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

$$f_{lj} - f_{jl} \leqslant u_{jl} y_{jl} \qquad \forall j, l \in S, \tag{5}$$

$$\sum_{i \in I} d_i x_{ij} \leqslant v_j \qquad \forall j \in S, \tag{6}$$

$$f_{jN} \leqslant M w_{jN} \qquad \forall j \in S, \tag{7}$$

$$y_{jl} \leqslant z_j, y_{jl} \leqslant z_l \qquad \forall j, l \in S, \tag{8}$$

$$y_{jl} \leqslant b_{jl} \qquad \forall j, l \in S, \tag{9}$$

$$\sum_{h=l+1}^{l_i} x_{ij_h^{(i)}} + z_{j_l^{(i)}} \leqslant 1 \qquad \forall l = 1, ..., L_i - 1, \forall i \in I, \tag{10}$$

$$x_{ij}, z_j, y_{jl}, w_{jN} \in \{0, 1\} \qquad \forall i \in I, \forall j, l \in S. \tag{11}$$

Objective function (1) accounts for the total cost of the network including installation cost c_j and costs p_j related to the connection of a **MAP** to the wired backbone. (2) forces each **TP** to be assigned to one active **CS** that covers it (see (3)). (4) is a classical flow balance set of equations while (5),(6) and (7) are sets of capacity constraints for, respectively, links, routers and gateways. A wireless link between two nodes exists only if they are both active (8) and neighbour (9). (10) imposes the assignment of a **TP** to the nearest active **BS** while (11) restricts the decision variables to take binary values.

Note that the above is an *optimal planning* formulation that does not take into account the temporal variations of the demand nor the dynamics of the coverage that are necessary in an efficient *operational* energy management scheme. Thus, to create the energy management framework, the above model is modified as follows:

- The objective function changes to recreate an energy efficient objective.
- The main philosophy of the model changes as there are no longer Candidate Sites but rather installed Base Stations at particular sites that could be put down according to the variations in demand.
- A dynamic assignment of users to coverage areas is enforced.
- System parameters are modified to account for the temporal notion of the operation.
- The decision variables reflect the fact that the equipment can be powered down at particular instants of time.
- Constraints are added to relate the dynamic assignment with the state (on or off) of the equipment.

4 Optimized framework for energy management

For simplicity, we first present a first optimal energy management model. Then, we introduce variations to the model that take into account different energy related elements that we want to study and that will be put into relevance in the analysis of the results.

4.1 An optimal energy management model

The main idea of the model is to decide which elements of the network should be turned off and at what instants of time so that energy consumption is minimized and the demand is always satisfied. For this, the model must also convey the delicate balance between operation dynamics and user coverage. We assume that the network has been previously built, that Base Stations have been installed and that the site of the TPs is known in advance. Therefore, we propose the following mathematical notation.

Sets:

I	the set of **TP**s
T	the set of time intervals
S	the set of BS, being **MR**s or **MAP**s
$G \subseteq S$	the subset of BS that are **MAP**s (gateways)
$J_h^{(i)}$	the subset of **BS**s covering **TP** i ordered by decreasing received power where h is the index of position inside the set

Input parameters:

$$a_{ij} = \begin{cases} 1 & \text{if the } \textbf{TP } i \text{ is covered by } \textbf{BS } j \\ 0 & \text{otherwise} \end{cases}$$

$$b_{jl} = \begin{cases} 1 & \text{if a wireless link between } \textbf{BS}\text{s } j \text{ and } l \text{ is possible} \\ 0 & \text{otherwise} \end{cases}$$

$$h_{it} = \begin{cases} 1 & \text{if } \textbf{TP } i \text{ is requesting traffic } (d_{it} > 0) \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

d_{it} traffic request of **TP** i at time t,

u_{jl} capacity of the link between **BS**s j and l,

v_j access capacity **BS** j can offer to its **TP**s,

L_i number of **BS** covering **TP** i

ξ_j power consumption of the device $j \in S$.

m capacity of Internet access of the **MAP**

Decision variables:

$$x_{ijt} = \begin{cases} 1 & \text{if } \textbf{TP } i \text{ is assigned to } \textbf{BS } j \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$z_{jt} = \begin{cases} 1 & \text{if } \textbf{BS } j \text{ is active at time } t \\ 0 & \text{otherwise} \end{cases}$$

f_{jlt} flow between **BS**s j and l at time t

f_{j0t} flow from **BS** j to *Node 0* at time t

We now explain each element of the optimal energy management model $(P1)$:

The objective function

$$\sum_{j\in S}\sum_{t\in T} z_{jt}\xi_j \Delta T \tag{12}$$

We assume that the power consumption of our devices is constant during each interval of time and equal to the previously defined ξ_j. Therefore, the energy consumption of a given **BS** j is obtained by multiplying ξ by the activity time length and the decision variable that indicates if the BS is active. The total energy consumption is then obtained by summing up over all BS and all intervals of time considered. The objective will be to minimize (12).

Assigment constraints

There are two type of assignment constraints. (13) imposes that at each time interval every **TP** is assigned to a **BS** and (14) requires the **BS** assigned to be active and to cover the given **TP**. These are important constraints in energy management given that they relate a time-varying covering functionality with a time-varying BS operation.

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

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

Flow conservation constraints

$$\sum_{l\in S}(f_{ljt} - f_{jlt}) + \\ + \sum_{i\in I} d_{it} x_{ijt} = f_{j0t} \qquad \forall j \in S, \forall t \in T \tag{15}$$

(15) is the classical set of flow balance constraints. The first term represents the difference between the ingoing and the outgoing traffic in the links among BSs that can be of different type (MAPs or MR). The term $\left(\sum_{i\in I} d_{it}x_{ijt}\right)$ is the traffic supply of the device to its TPs. Finally, the last term f_{j0t} represents the flow between the **MAP**s and the Internet, considered as special node 0.

Capacity constraints

There are several types of capacity constraints. Constraints (16) insure that the capacity of each node is respected whereas (17) refer to the capactiy of the link. (18), on the other hand, imply that the capacity of the Internet access of each **MAP**s must be m.

$$\sum_{i\in I} d_{it} x_{ijt} \leqslant v_j \qquad \forall j \in S, \forall t \in T \tag{16}$$

$$f_{ljt} + f_{jlt} \leqslant u_{jl} b_{jl} z_{jt} \qquad \forall j, l \in S, \forall t \in T \tag{17}$$

$$f_{j0t} \leqslant m \qquad \forall j \in G \subseteq S, \forall t \in T \tag{18}$$

Best assignment constraints

$$\sum_{h=l+1}^{l_i} x_{iJ_h^{(i)}t} + z_{J_l^{(i)}t} \leqslant 1 \qquad \forall l = 1, ..., L_i - 1, \\ \forall i \in I, \forall t \in T \tag{19}$$

This set of constraints forces every **TP** to be assigned to the best active device.

Binary constraints

Finally, we have the constraints that impose binary values to the decision variables.

$$x_{ijt}, z_{jt} \in \{0, 1\} \qquad \forall i \in I, \forall j, l \in S, \forall t \in T \tag{20}$$

Summarizing model $P1$ can be presented as follows:

$$\min \quad (12)$$
$$\text{s.t. } (13) \text{ to } (20).$$

4.2 The covering-relaxed Problem

We have also developed some variants of the proposed model presented above, not only to have a basis for comparison but also to be able to grasp some of the particular features of the energy management situation.

The covering-relaxed model $\underline{P1}$ is obtained relaxing the assignment constraints of $P1$. Let us focus on constraints (13):

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

This set of constraints imposes that every **TP** must be assigned to one and only one **BS** and, since (14) forces to assign a terminal to a device only if it is active and it covers it, we can derive that each **TP** is assigned to, and subsequently covered by, one active **BS**.

We want to restrict the application field of the covering constraints only to active **TP**s and this will result in a lack of coverage of those terminals that are not active. Thus, the previous sets of constraints (13 and 14) are relaxed and replaced by the following:

$$\sum_{j \in S} x_{ijt} = h_{it} \qquad \forall i \in I, \forall t \in T \tag{21}$$

Then, $\underline{P1}$ can be defined as follows:

$$\begin{array}{c} \min \quad (12) \\ \text{s.t. } (15) \text{ to } (21). \end{array}$$

Since $\underline{P1}$ is a relaxation of $P1$ its objective function will be a lower bound that would be used in the analysis of the results presented in the next Section.

4.3 Additional problem variations

Two additional situations will be used for comparison purposes: one is the total absence of traffic, in which no traffic is requested from any of the TPs ($d_{it} = 0 \;\; \forall i \in I, \;\; \forall t \in T$) and another one in which all **TP**s are active and demanding the maximum amount of traffic ($d_{it} = 10Mbps \;\; \forall i \in I, \;\; \forall t \in T$). We call the first case the no-traffic problem $P1_0$ and the second one, the $f$ull-traffic problem $P1_f$.

The objective functions of these two cases will provide us with useful comparison bounds that will be discussed in the results Sections.

5 Resolution approach and results analysis

To test our models and extract the most relevant information we first created an instance generator, then we produced a large set of instances that were optimized using AMPL and CPLEX. Followed the comparative results for the four variations of the problem.

5.1 Instance generation

Generating feasible WMN instances is a delicate process since we need to use network topologies that can represent possible network deployments provided during the design phase. Thus, we developed an instance generator program (IG) in *C++* that takes into account the following issues:

- the topology, the dimension of the area analyzed and the numbers of **TP**s and **BS**s to place;
- the architecture, in particular the placement of all devices according to certain controls;

kind of WMN	dimension (m)	tps	BS (MAPs)
small	1000	60	16(2)
medium	1500	130	40(3)
large	2500	240	64(5)

Table 2: Types of **WMN** used in our optimization analysis

- specific values of the technology used such as access capacity of the **BS**s, capacity of the wireless links, covering rays and so on;
- a random traffic profile with a different level of congestion for each time interval.

Once IG is applied, the resulting instance must have:

- a random topology, according to certain constraints,
- feasible assignments,
- realistic values.

The first item above refers to the fact that the topology and the architecture are generated randomly inside a predetermined area. The second one refers to the fact that each BS must be able to provide the **TP**s with the maximum traffic amount possible and the third one refers to the technologically feasible values assigned to the different input parameters. Moreover, specific controls are added to the random generation to insure network feasibility.

5.2 Input assumptions and parameter values

All the optimization instances presented the following input values

- $R_1 = 450$m, is the covering ray for the communications between **MR**s or **MAP**s;
- $R_2 = 250$m, is the covering ray for the communications between a **BS** and the terminals associated to it;
- $v_j = 40$ **Mbps**$, \forall j \in S$, $u_{ij} = 300$ **Mbps**$, \forall i, j \in S$ and $m = 10$ Gbps;
- $\xi_j = 15W$ if j is a **MR** and $18W$ if j is a **MAP**.

Moreover, three different kinds of WMN were generated. Their features are portrayed in Table 2. The first column refers to the name that will be used throughout the analysis to identify the type of instance. The second corresponds to the size of a square area. The third is the number of TPs available in the instance. Finally, in the third column we have the number of installed BS (MR or MAPs), the MAPs being identified in parenthesis.

We have generated 150 instances for each kind of **WMN** presented in Table 2 and all the mean results over the 150 instances will be shown in Table 3. To understand the table, we need to define some additional notation.

Let β be the consumption of a WMN when all BS are active; c be the value of objective function (12); α the percentage of savings when compared with the consumption when all BS are active ($\alpha = 1 - c/\beta$) and γ the total traffic requested by all terminals .

By abuse of notation, we will also use the following subscript to refer to particular values:

	mean value of the parameters		
	small	**medium**	**large**
β (Wh)	5904	14616	23400
c_f (Wh)	5875	13535	23171
c_0 (Wh)	2751	6099	11845
	Standard traffic		
	small	**medium**	**large**
γ (Mbps)	1501	3252	6012
c (Wh)	3222	6876	13627
$\underline{c}$ (Wh)	2883	6036	12283
α (%)	45.414	52.956	41.762
$\underline{\alpha}$ (%)	51.157	58.699	47.505
θ (%)	0	0.755	2.448
$\underline{\theta}$ (%)	0	1.777	4.737
	Busy traffic		
	small	**medium**	**large**
γ (Mbps)	2461	5320	9843
c (Wh)	4140	8985	16946
$\underline{c}$ (Wh)	3866	8314	15915
α (%)	29.877	38.525	27.579
$\underline{\alpha}$ (%)	34.511	43.116	31.984
θ (%)	0	0.565	1.834
$\underline{\theta}$ (%)	0	1.739	3.771

Table 3: Numerical results of the optimization process

– t, the value at time interval t, (i.e. c_t),
– f, the value in the full-traffic situation (i.e. c_f),
– 0, the value in the no-traffic situation (i.e. c_0).

Also note that the underline will refer to the values associated to the covering-relaxed model.

It is important to point out the difference between β and c_f: the first is the consumption of a **WMN** without optimization, that is, the sum of all the installed **BS** consumption while the second is the consumption evaluated as the objective of problem $P1_f$, that is, the consumption in the optimized case when all **TP**s are active and demand the maximum value of traffic. It is then clear that while β depends solely on the number of **BS**, regardless of their location, c_f is related to the TP demand and, therefore,depends on the network topology.

5.3 Energy performance and network topology

From Table 3 the first thing to point out is that the difference between β and c_f is very low, around 2% for the small instances, 7% for medium ones and 1% for the large ones. This means that the instances are well generated and, in particular, that the total number of **BS**s is realistic. There are no unnecessary devices installed but all are used to guarantee the activity of the networks in the hypotheses of all terminals being active and generating the maximum amount of traffic (10 Mbps).

Looking at the optimization gap values θ and $\underline{\theta}$ given in the Table, one can see that for the small networks all solutions are optimal and that all gaps are under a tolerance

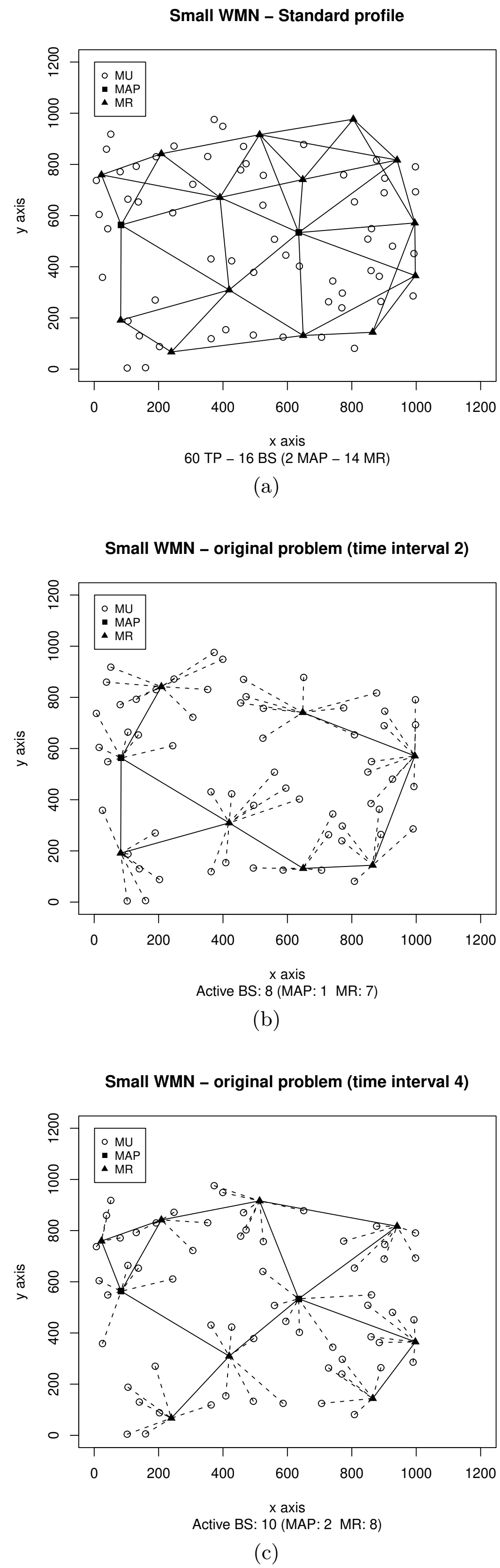

Figure 2: An example of small **WMN** represented first with all active devices, then in two different time intervals

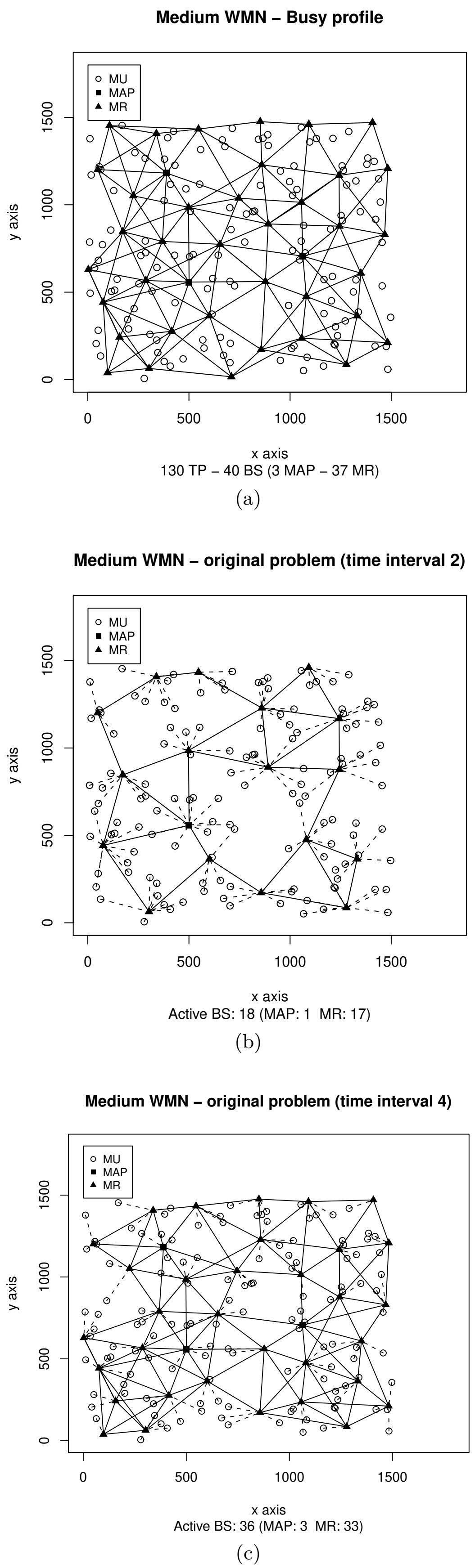

Figure 3: An example of medium **WMN** represented first with all active devices, then in two different time intervals

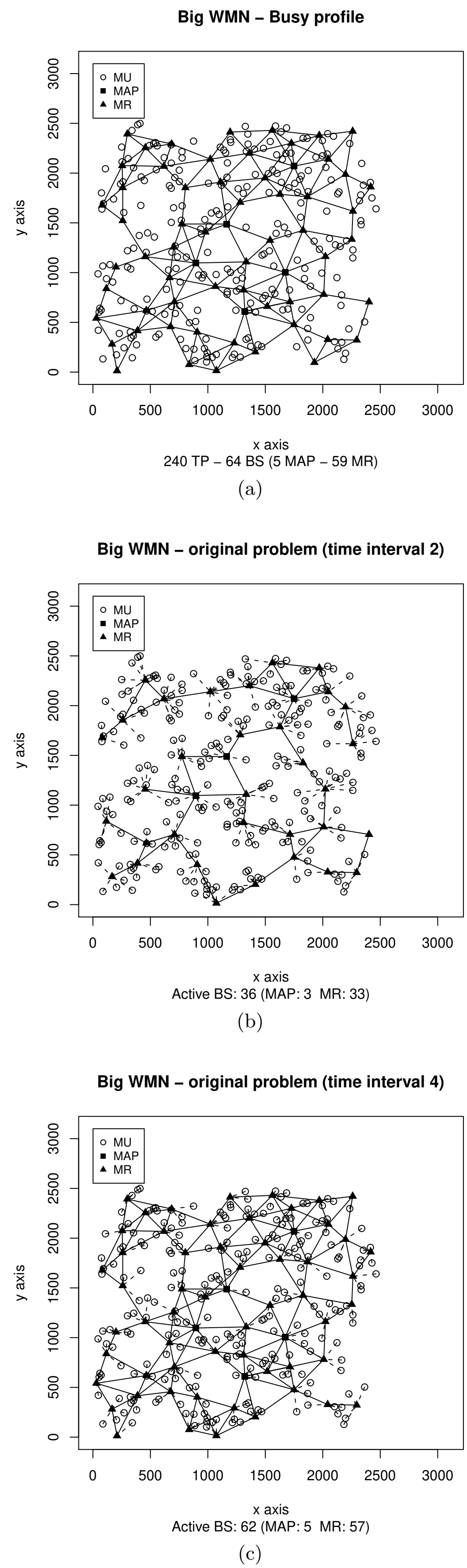

Figure 4: An example of a large **WMN** represented first with all active devices, then in two different time intervals

threshold of 5% even for medium and large networks, which implies that these are problems that can be solved fairly well with direct optimization methods.

Regarding the value of α and $\underline{\alpha}$, that is, the mean energy gains obtained when solving the main optimization problem or the covering relaxed problem, we can see that, for the standard traffic we can easily reach 40% of savings whereas for the heavy traffic the savings are closer to 30%. In all the cases, there is at least a 5% difference in savings with the solution of the covering relaxed problem.

To portray the network topologies found from the optimization model, we can see the three network examples in Figures 2,3 and 4. Figures 2-a, represents the initial small network that represents 60 TPs and 16 installed BSs, we can see that when the optimization model is applied, the topology is reduced to 8 BS for the second interval, which has low demand, and to 10 BS for the fourth interval, which has high demand (see figures 2-b and 2-c, respectively). The same trend can be seen by examining figures 3 and 4. One can see that in all the cases, the networks are less connected for the second and fourth intervals, thus requiring fewer resources. It can be appreciated that in all cases, the topology presents more links in the fourth than in the second interval but fewer links than the distribution system, showing the difference it makes to optimize the energy consumption.

A more detailed view of the energy management features and its relationships with network topology can be appreciated by inspecting Tables 4, 5 and 6. The Tables present the minimum, average and maximum number of base stations and MAPs found for each interval of time, over the 150 instances that were run, for normal and heavy traffic and for the three types of network sizes, respectively. In the Tables we have bolded the results for which the upper bound (on the number of BS or MAPs) is equal to the initial problem. We can see that, with respect to the BS of the small network (see Table 4) only two instant of times ($t = 4, 6$) in the busy case present the maximum number of BS up. Remarkably, in all the other instances and cases, there is a considerable number of BS shut down. For the large network (Table 6), the situation occurs in just one interval, for ($t = 4$), also for the busy case. However, for the medium size network (see Table 5),no interval or case, among the 150 instances produced with different demand levels needed the maximum number of base stations. This shows the power of optimizing the energy management.

With respect to the MAP, the opposite occurs: in almost all intervals and cases the maximum number of MAPs is obtained, except for interval ($t = 3$) for the large network, heavy traffic and covering relaxed problem in which a lower number of MAPs were installed in the worst case.

5.3.1 Energy profiles

In Figures 5, 6 and 7 the mean consumption profiles per interval over all the small, medium and large network instances, respectively, are provided. The subfigures (a) represent the case for standard demand and (b) for busy demand. In every one of those figures one can appreciate four different consumption levels: that for the original problem $P1$, the full traffic problem $P1_f$, the covering-relaxed problem $\underline{P1}$ as well as the no traffic one $P1_0$.

The *full-traffic* consumption, that is to say the energy necessary to feed the **WMN** with all terminal active and demanding for the maximum value of traffic (γ), is the upper bound for the consumption in all the cases. There are, however, two lower bounds, the one derived by the relaxation of the covering constraint and the one related to the absence of traffic. What is interesting is that these two bounds appear at different intervals of time. For the cases with *standard demand*, the value of the objective function of the covering-relaxed problem is the lower bound for the first three and the last intervals, all of which present a traffic demand below 50%. The value of the energy objective for problem $P1_0$, which represents the case in which there is absence of traffic, is, on the other hand, the lower bound for all the other intervals. For the cases with *busy demand*, the covering-relaxed problem will be the lower bound only for the first two intervals. In all cases, during the intervals of normal operation, the covering-relaxed problem tended to produce the same optimization result than the original case. This means that when the demand is close to the nominal one, there is no gain in relaxing the covering constraints. On the other hand, when the demand is low, relaxing that constraint can yield important gains even when compared with the energy optimized problem.

In all the cases the optimization model produces significant energy savings with respect to the full traffic problem. We also observe that the variance of those savings is larger for the busier profiles.

The relationship in energy savings are clearer when the saving percentage α is portrayed for each interval considered, such as in Figure 8 where the case for large instances is presented. We can see that when comparing the original problem with the relaxation $\underline{P1}$, the latter is an upper bound on energy savings. We can also see in Figure 8 that the curves are very close to the aforementioned bound.

The quite high values of α, with both traffic profiles, are a good measure of the *green impact* this model could have if applied to a large scale of **WMN**s. Furthermore Figure 8 shows that, as expected, the lower the traffic the higher is the percentage of energy savings. In fact the highest values of α are in the night hours when most of the **TP**s are inactive.

Even though during the low traffic periods (time intervals 1 and 2) we have the maximum values of saving, we can note that in those time intervals $\alpha << \underline{\alpha}$. The reason is the guarantee of covering all the terminals (that is not present in the relaxed problem) that forces to activate **BS**s even when there is no-traffic.

Our final results are portrayed in Figure 9 that shows the curve of consumption versus different levels of traffic for the two different traffic profiles. The consumption for zero traffic is given by c_0 for $P1$ while it is zero for $\underline{P1}$. We recall that for that case, the assignment of a **BS** is assured only to active **TP**, thus, if there is no traffic, it means that all the **TP** are inactive and consequently all the routers and gateways are switched off. We can also note that the difference between

	Small WMN- Min/Average/Max values													
	Without optimization		Normal											
			$P1$						$\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	16	2	7	8,0	9	1	1,1	**2**	5	6,6	9	1	1,1	**2**
2	16	2	7	7,8	9	1	1,1	**2**	1	4.1	7	1	1,1	**2**
3	16	2	7	8,0	9	1	1,1	**2**	5	7,2	9	1	1,1	**2**
4	16	2	9	10,8	14	1	1,2	**2**	9	10,8	14	1	1,2	**2**
5	16	2	7	8,8	12	1	1,1	**2**	7	8,6	12	1	1,1	**2**
6	16	2	8	9,6	12	1	1,1	**2**	8	9,5	12	1	1,1	**2**
7	16	2	7	8,3	10	1	1,0	**2**	6	7,8	10	1	1,1	**2**
8	16	2	7	8,1	10	1	1,1	**2**	5	7,4	10	1	1,1	**2**
	Without optimization		Busy											
			$P1$						$\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	16	2	7	8,4	10	1	1,1	**2**	5	7,3	9	1	1,1	**2**
2	16	2	6	7,7	9	1	1,1	**2**	1	4.2	7	1	1,1	**2**
3	16	2	8	9,2	11	1	1,1	**2**	5	8,5	11	1	1,1	**2**
4	16	2	15	15,9	**16**	1	1,9	**2**	15	15,9	**16**	1	1,9	**2**
5	16	2	9	12,6	15	1	1,4	**2**	9	12,5	15	1	1,4	**2**
6	16	2	12	14,9	**16**	1	1,8	**2**	12	14,9	**16**	1	1,8	**2**
7	16	2	8	11,0	14	1	1,2	**2**	8	10,8	14	1	1,2	**2**
8	16	2	8	9,7	13	1	1,1	**2**	6	9,3	13	1	1,1	**2**

Table 4: Number of active BSs for the small **WMNs**

	Medium WMN- Min/Average/Max values													
	Without optimization		Normal											
			$P1$						$\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	40	3	14	17,3	19	1	1,1	**3**	11	13,9	17	1	1,1	**3**
2	40	3	14	17,1	19	1	1,1	**3**	5	8,7	12	1	1,4	**3**
3	40	3	15	17,5	19	1	1,1	**3**	13	15,1	18	1	1,1	**3**
4	40	3	20	23,1	27	1	1,4	**3**	20	23,1	27	1	1,4	**3**
5	40	3	17	19,0	22	1	1,2	**3**	16	18,1	21	1	1,1	**3**
6	40	3	18	20,7	25	1	1,3	**3**	18	20,4	25	1	1,2	**3**
7	40	3	16	18,1	21	1	1,1	**3**	14	16,7	19	1	1,1	**3**
8	40	3	15	17,7	20	1	1,1	**3**	13	15,7	20	1	1,2	**3**
	Without optimization		Busy											
			$P1$						$\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	40	3	16	18,4	21	1	1,1	**3**	12	15,7	20	1	1,3	**3**
2	40	3	15	17,3	20	1	1,1	**3**	5	9,2	13	1	1,5	**3**
3	40	3	17	19,9	24	1	1,3	**3**	15	18,2	22	1	1,3	**3**
4	40	3	34	36,8	39	2	2,8	**3**	34	36,8	39	2	2,8	**3**
5	40	3	23	27,2	32	1	1,8	**3**	23	26,9	32	1	1,7	**3**
6	40	3	28	32,2	36	1	2,3	**3**	27	32,1	36	1	2,3	**3**
7	40	3	20	23,9	28	1	1,5	**3**	19	23,2	28	1	1,5	**3**
8	40	3	18	20,9	24	1	1,3	**3**	16	19,5	24	1	1,2	**3**

Table 5: Number of active BSs for the medium **WMNs**

	Large WMN- Min/Average/Max values													
	Without optimization		Normal $P1$						Normal $\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	64	5	33	35,1	38	1	2,4	**5**	25	29,9	34	1	2,6	**5**
2	64	5	32	34,6	38	1	2,2	**5**	13	20,3	28	1	2,8	**5**
3	64	5	33	35,4	40	1	2,5	**5**	28	31,7	37	1	2,6	**5**
4	64	5	40	43,9	49	1	2,9	**5**	40	43,8	49	1	3,0	**5**
5	64	5	32	37,4	42	1	2,7	**5**	32	36,3	42	1	2,6	**5**
6	64	5	36	40,2	44	1	2,7	**5**	36	39,7	44	1	2,6	**5**
7	64	5	33	36,2	40	1	2,6	**5**	31	34,1	38	1	2,7	**5**
8	64	5	32	35,5	39	1	2,5	**5**	29	32,5	36	1	2,5	**5**
	Without optimization		Busy $P1$						Busy $\underline{P1}$					
time	**BS**	**MAP**	**BS**			**MAP**			**BS**			**MAP**		
			Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max
1	64	5	32	37,2	44	1	2,5	**5**	28	32,8	39	1	2,7	**5**
2	64	5	32	35,3	39	1	2,3	**5**	14	23,2	30	1	2,6	**5**
3	64	5	36	39,1	43	1	2,7	**5**	31	36,5	42	1	2,8	4
4	64	5	62	63,3	**64**	4	4,9	**5**	62	63,3	**64**	4	4,9	**5**
5	64	5	45	50,3	57	1	3,3	**5**	44	50,3	57	1	3,3	**5**
6	64	5	55	59,2	63	3	4,6	**5**	55	59,2	63	3	4,6	**5**
7	64	5	41	44,0	51	1	3,0	**5**	39	44,0	50	1	2,9	**5**
8	64	5	36	38,7	47	1	2,9	**5**	34	38,7	45	1	2,8	**5**

Table 6: Number of active BSs for the large **WMNs**

$P1$ and $\underline{P1}$ decreases while traffic increases till becoming null at a point that represents a sort of *saturation* value of traffic. After that there is a *proportionality* between traffic and consumption.

6 Conclusion

In this paper we presented a model for energy saving that takes advantage of the flexibility of WMN and of a careful management of BS operation. We created an instance generator and prepared a substantial set of instances to evaluate the model and compare them with other modelling variations.

We found that, as expected, great energy savings can be achieved while guaranteeing the smooth operation of the wireless network. We also found that greater savings can be achieved by relaxing the all-over covering constraints by carefully re-assigning only the active traffic points to the most appropriate active base stations. We were able to assess, through a systematic study, that the amount of savings produced by using an optimal energy management scheme such as the one proposed, runs around 40% for normal conditions, and 30% for heavy traffic conditions. The relaxation of the covering constraint producing at least 5% more savings.

In conclusion, combining the flexibility of Mesh networks with the optimization of the energy management can produce networks that work in their required QoS range but with a significant power saving with respect to their current operation.

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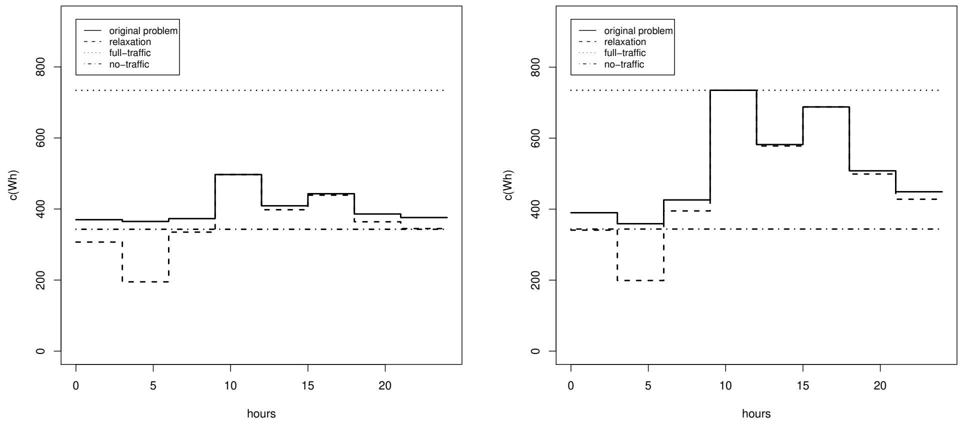
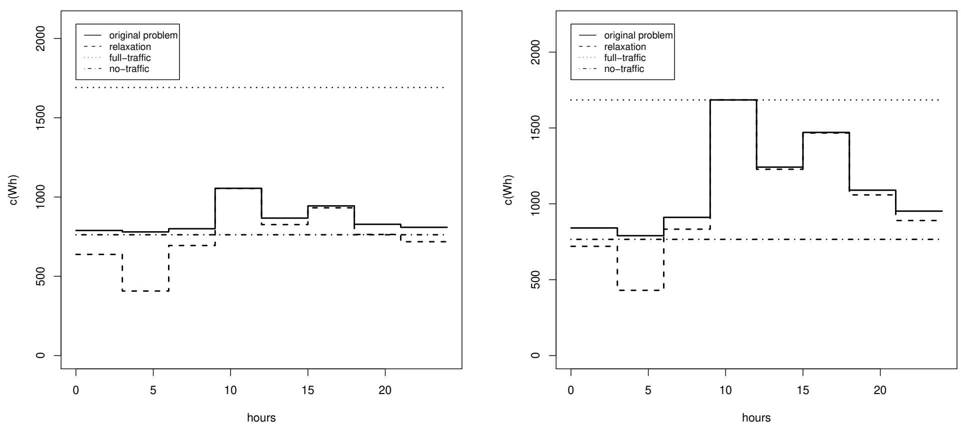


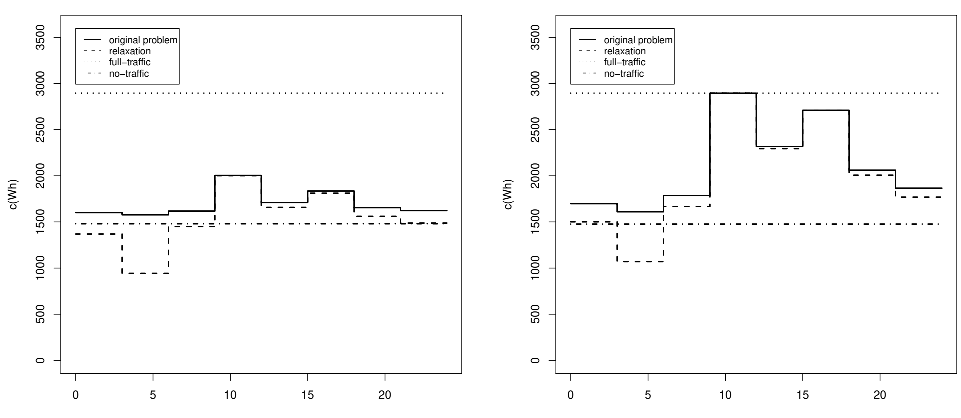
(a) (b)

Figure 5: Average values of energy consumption for 150 small **WMN**s with both traffic profiles: (a) standard and (b) busy



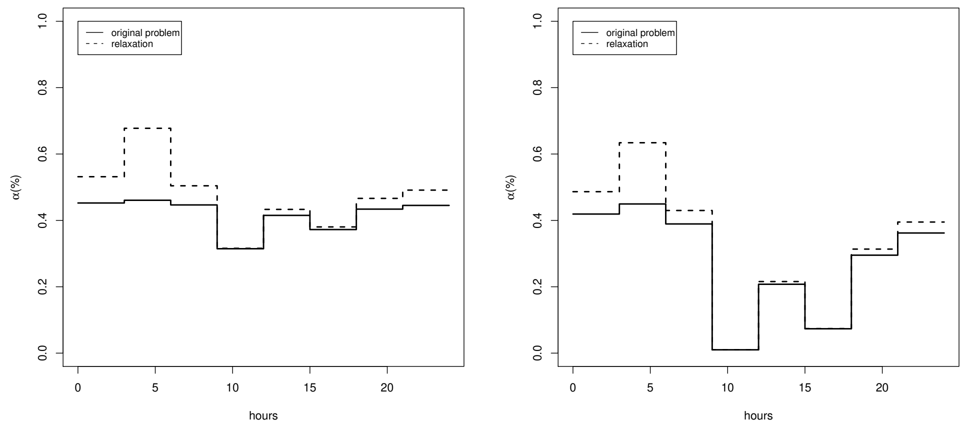
(a) (b)

Figure 6: Average values of energy consumption for 150 medium **WMN**s with both traffic profiles: (a) standard and (b) busy



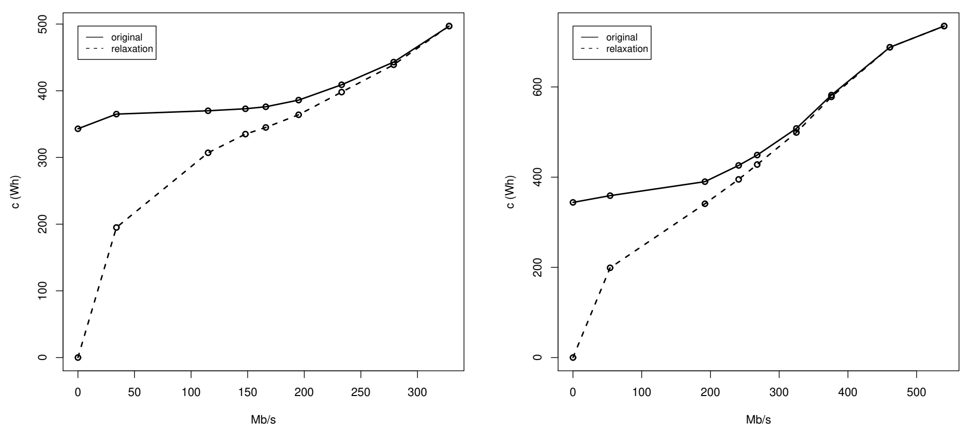
(a) (b)

Figure 7: Average values of energy consumption for 150 large **WMN**s with both traffic profiles: (a) standard and (b) busy



(a) (b)

Figure 8: The percentage of energy saved in 150 large **WMN**s with both traffic profiles: (a) standard and (b) busy



(a) (b)

Figure 9: The curve of consumption according to traffic for 150 small **WMN**s with both traffic profiles: (a) standard and (b) busy