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Energy-savings in Wireless Mesh Networks in a time-variable context

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List of Acronyms

ACEEE	American Council for an Energy-Efficient Economy
ALR	Adaptive Link Rate
AMC	Adaptive modulation and coding
AP	Access Point
BS	Base Station
CAPEX	Capital Expenditures
CDMA	Code Division Multiple Access
CMOS	Complementary metal-oxide semiconductor
CPU	Central processing unit
CS	Candidate Site
CSMA	carrier sense multiple access
EU-ETS	emissions trading system
FDD	frequency-division duplex
GHG	greenhouse gases
HVAC	heating, ventilation and air conditioning systems
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronic Engineers
IG	Instance Generator
LAN	Local Area Network
MAP	Mesh Access Point

MILP	mixed integer linear programs
MMT	Million Metric Tons
MR	Mesh Router
MU	Mesh User
OH	overhead
OPEX	Operational Expenditures
OS	Operating system
PCH	Planning Capacity with Hyperbolic formulation
QoS	Quality of Service
RF	Radio Frequency
RoD	Resources-on-Demand
SEAR	Survey, Estimate, Adapt, Repeat
TP	Test Point
VMM	virtual machine monitor
VPS	virtual private servers
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Networks
WoA	wake-on-arrival

Abstract

Italiano

Il consumo energetico nelle reti di Telecomunicazioni sta diventando un problema di enorme rilevanza nello scenario globale e, tra tutti i settori, quello dell'accesso - ed in particolar modo la parte senza fili - é responsabile della maggior parte della spesa di energia elettrica. Le reti wireless stanno incrementando la loro diffusione anche nell'infrastruttura dorsale dei sistemi cellulari a causa principalmente dei bassi costi e della facilitá di sviluppo. In questo contesto le Wireless Mesh Networks (WMN) sono considerate tra le risorse piú idonee per la loro versatilitá che permette configurazioni flessibili. In questo lavoro di tesi noi combiniamo la flessibilitá delle WMN con l'esigenza di riduzione dei consumi energetici presentando un modello d'ottimizzazione per la gestione delle reti che prende in considerazione il compromesso tra i requisiti energetici e la variazione della domanda. Sono presentati inoltre l'approccio usato per la risoluzione e una profonda discussione sulla gestione del consumo energetico nelle reti WMN.

English

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 thesis 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.

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 growth of Internet traffic that is pushing huge investments around the world for increasing communication infrastructures in the coming years.

Indeed ICT is said to be responsible for a percentage of the world energy consumption that ranges from 2% to 10%.

Among Internet related networking equipment, the access is 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 [35, 36].

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 (WMNs) [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 [37, 9]. In WMNs 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 this thesis 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 energy in a time varying context by dynamically selecting a subset of mesh BSs 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.

In this thesis, 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 modelling of the energy minimization problem based on Mixed Integer Linear Programming (MILP), and solve it to the optimum.

The work is subdivided as follows: chapter 1 is a survey on the climate change issue and the energy saving opportunities provided by the world of ICT in favour of other sectors of industry, chapter 2 presents the general aspects of mathematical optimization applying them in well known problems of wireless network planning, chapter 3 is a review of the literature concerning *green networking* in both wired and wireless networks, chapter 4 and 5 describe respectively the analysed system and the mathematical formulation of the optimization model presented along with three little variations. Then follow chapter 6 with the resolution approach, chapter 7 with the discussion of the numerical results and chapter 8 with the conclusions.

Chapter 1

The climate change and ICT opportunities

1.1 The climate change

The latest studies concerning environment and pollution, as said in the preface, have alarming results. In the next decade, climate change will become a matter to be seriously taken into account and will influence the political strategies and the lives of all human beings. The accumulation of GHG in the atmosphere is reaching a very high and worrying level.

In figure 1.1 we can note that U.S. CO_2 emissions are expected to grow from $5,980$ million metric tons (MMT) in 2007 to 6,380 MMT in 2020. The ICT industry is responsible for a percentage of 2.5% of overall emissions in 2007 and this percentage is expected to increase in 2020 to the value of 2.8% (data from [4]).

The first relevant thing is that the annual growth rate of the ICT emissions is 1.4% and it is almost three times as much as the expected growth rate of total U.S. emissions.

1.2 The role of ICT

As said in the previous section, ICT will have a leading role in this very interesting issue of a green renewal of the world. ICT industry's carbon dioxide global emissions are supposed to increase from 150 MMT of CO_2 in 2007 to 180 in 2020 (see figure 1.2).

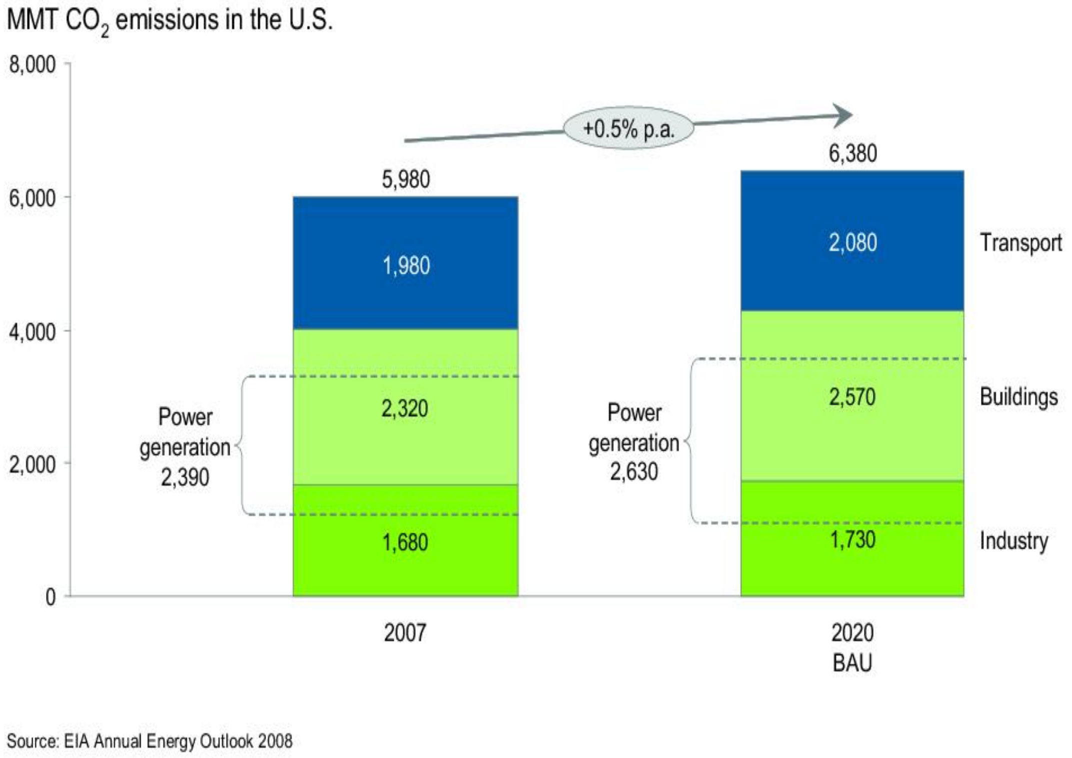


Figure 1.1: U.S. carbon emissions baseline

There are many opportunities for the ICT industry to provide energy efficiency like replacing goods and services with virtual devices and even yielding new and smarter technologies. *GeSI*[1] has pointed out the following issues:

- create a worldwide acknowledged report over the carbon footprint of ICT products and services
- highlight the climate change issues in the supply chain work of ICT industry in order to reconsider the manufacturing process for electronic equipment
- guarantee the environmental issues to be taken into account when fixing the technical standards of the industry
- work together with the organizations to gain potential CO_2 reductions acting in several opportunity areas

---

[1] an international strategic partnership of ICT companies and industry associations committed to creating and promoting technologies and practices with the aim of an economic, environmental and social sustainability

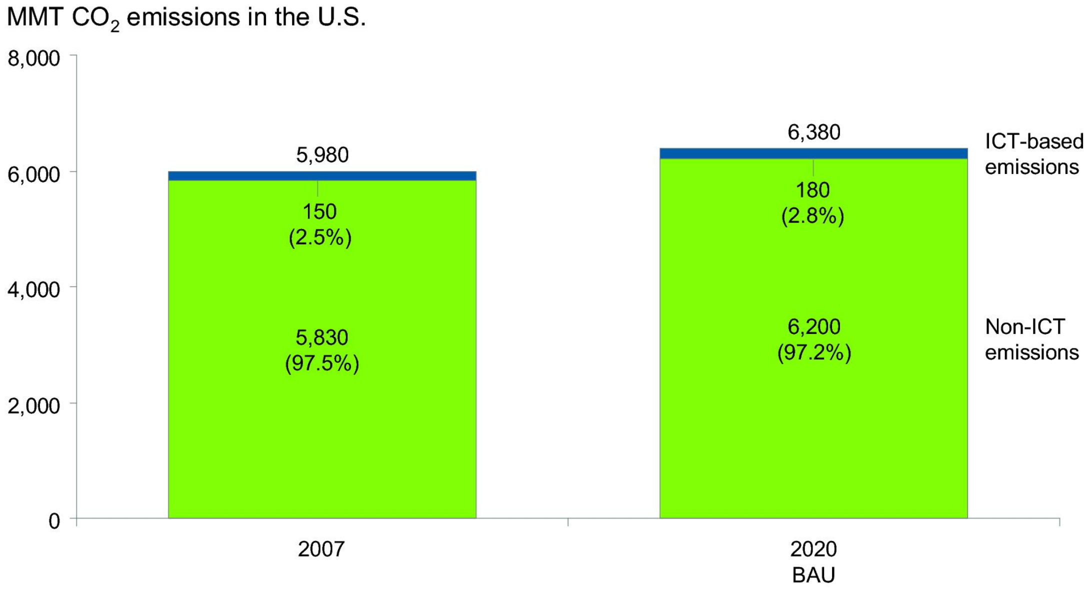
- cooperate with public policy makers to set the most effective fiscal and regulatory frameworks to enhance energy efficiency and to reduce emissions.

The last point consists in a policy of monetization of carbon emissions. Indeed economic incentives related to reduction in emissions will enhance the adoption of energy aware techniques because money is always a key parameter in the project phase of every industry and these techniques will be derived from ICT sector.

U.S. is deeply involved in this issue thanks to president *Barack Obama* and his aggressive policy with very prohibitive targets.

In Europe this kind of reward policy for energy efficient companies has already been built up through an *emissions trading system* (named EU-ETS) which since its implementation in 2005 has enabled only a thin reduction of 5% in all European GHG emissions from the business-as-usual scenario.

A second phase with tighter caps is expected to allow higher reductions.



Source: GeSI and the Climate Group, “Global Smart 2020 report”, 2008; EIA Annual Energy Outlook 2008; BCG analysis. In assessing ICT’s carbon footprint, the use and operation of all ICT equipment (including emissions from cooling data centers) were considered, but the embedded carbon was not. To breakout U.S. ICT emissions from U.S. and Canada total, share of U.S. GDP in 2020 was used from Euromonitor

Figure 1.2: U.S. ICT industry’s emissions

ICT sources of consumptions can be summarized as follows:

- PCs and peripherals

- services
- Telecommunications networks and devices

The ICT industry is supposed to reduce its own emissions investing in innovation and advanced technologies aiming at reducing the 60% of the emissions brought by increased demand.

These innovations consist of:

data centers: server virtualization ([38]), the choice of efficient devices and adequate protocols concerning heating and cooling

PC's efficiency: replacement of energy-hungry desktops with laptops and thin clients, the switching of all cathode ray tube monitors with *LCD* screens and a smarter standby power management

Telecommunications Networks and devices' efficiency: a more effective use of the resources avoiding the underemployment, reduction of standby power and widespread application of network optimization algorithms

As well as the contribution to the consumptions given by the three outlined points before, ICT can provide solutions to other industry sectors to minimize energy wastes and to reduce GHG emissions coming from the rest of the economy.

In particular ICT is the source of one of the most powerful resources, *information*, namely it gives people an idea of how much energy they are using in order to give them the instruments to act in a smarter way. So ICT does not only use mechanical devices but even the human mind.

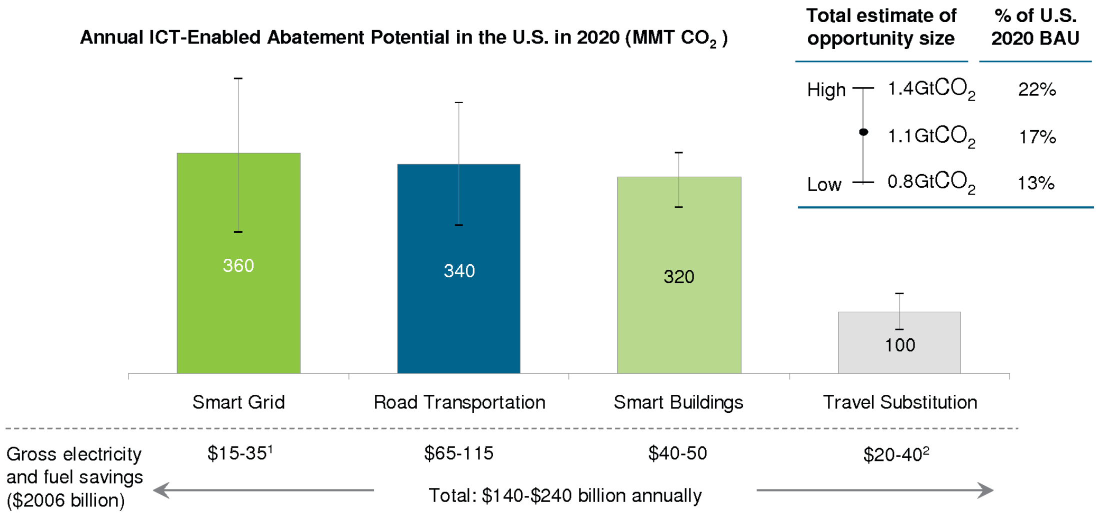
It is accepted that people are responsible of great wastes but they could also bring relevant improvements in our field of interest with a little more awareness.

An interesting datum supporting the leading role of ICT is an estimate of the *American Council for an Energy-Efficient Economy* (ACEEE) that reported that *for every* $1kWh$ *of energy consumed by ICT the U.S. economy increases overall energy savings by a factor of* 10.

ICT can also develop coordination among several consumers of services improving the use of the resources: this is the case of *car-sharing* for example.

All these capabilities make ICT a leverage for the process of renewal for a more sustainable and greener world.

1.3 ICT enabled solutions



1. Gross savings due to integrating renewable energy not included in SMART 2020 global analysis and left out of U.S. analysis as well. Renewable energy is a direct substitute, not an energy efficiency savings.
2. Only jet fuel savings were included in the analysis for virtual meetings. Other savings from virtual meetings not considered.
Note 1: Buildings and Power Generation have different baselines although coincidently the size rounds up to the same figure
Note 2: Gross savings do not consider required investments to implement the opportunities
Source: EIA; EPA; DOE; NAIOP; NETL, EPRI; GeSI and the Climate Group, "Global Smart 2020 report", 2008; Expert Interviews; EITCA; BCG Analysis

Figure 1.3: Estimated ICT-enabled CO_2 abatement potential in the U.S.

[4] determined four main fields where ICT can enable a great reduction in energy consumptions and GHG emissions:

- smart grid
- road transportation
- smart buildings
- travel substitution

1.3.1 Smart grids

Smart grids are electricity networks that are dynamically configured according to informations brought by its nodes in order to allocate the resources in a more effective way reducing the wastes. They have a distributed architecture instead of the centralized old one. The U.S. electrical network has been loosing efficiency in the last 25 years, in particular the average thermal efficiency of America's power plants is still around 33%, value of the year 1960. At that time U.S., with its 10000 power plants and 20000 miles of high voltage transmission lines, were the forefront of the sector but the incredible growth experienced by America since those years has not concerned the electrical sector. In fact there have not been improvements in technologies and infrastructure and this resulted in an increasing grid congestion generating the doubling of *transmission and distribution* (T & D) losses form 5% in 1970 to 10% in 2001.

Aside from this situation of the electrical grid, the habits of inhabitants changed very rapidly in the last years so that the demand of energy supply has really increased requiring a strong policy of renewal of all the entire network.

Moreover emissions from the generation of electrical power are growing very fast and its estimated value of 2360 MMT of CO_2 by 2020 is alarming.

The opportunity of potential reduction in 2020 enabled by ICT in the sector of *Smart Grid* ranges from 230 to 480 MMT of CO_2 with a mean value of 360 (see figure 1.3). Figure 1.4 outlines the opportunities of ICT to reduce emissions in the Smart Grid context.

In particular ICT can be useful to balance the variable amount of renewable energy with the demand through:

- software algorithms
- remote monitoring of production
- pool distributed sources into a *virtual power plant*

Furthermore ICT can help to reduce T&D losses with a remote monitoring of the performance and a dynamic allocation of the resources implying:

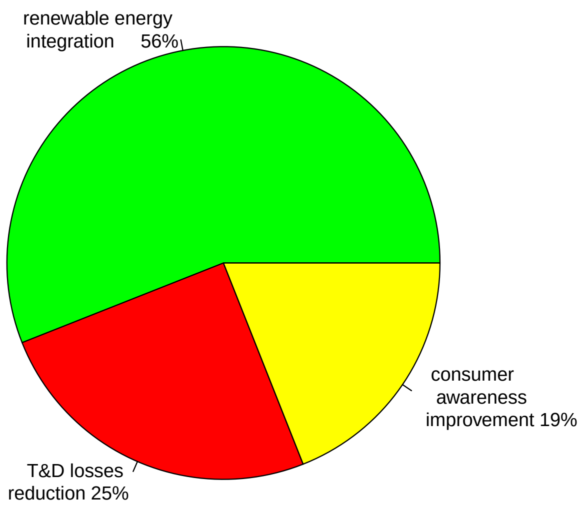


Figure 1.4: Pie chart of ICT-enabled potential reduction in the Smart Grid sector

- automatic detection and pre-emption of faults
- adaptive voltage control
- extended granularity of information for the grid's remote control systems

It is possible to enhance the consumers' sensibility providing them with information on prices and usage through the use of smart meters, intelligent thermostats and appliances that set usage according to prices and web-based interfaces to manage and analyse usage.

1.3.2 Road transportation

Another area of interest where ICT can enable large reductions in emissions is *road transportation*, that is to say everything concerning the movement of people and good in the street of the world and in particular we will analyse the case study of U.S. as reported by [4].

Road transportation emissions are expected to reach in 2020 the value of 1580 MMT of CO_2. ICT can potentially eliminate an amount of CO_2 emission that ranges from 240 to 440 MMT (15%-28%).

There are mainly two kinds of transportation:

- *individual*
- *commercial*

The problems dealing with the first are as well as the emissions, traffic congestions, scarce usage of public transportation, low efficiency of the vehicles, gas cost and so on. While commercial transport in addition to the aforementioned issues has underemployment of the resources since it is estimated that 25% of all trucks on the road are empty and their routes are not optimized causing unnecessary miles of travel, gas consumption and CO_2 emissions.

ICT can focus its intervention in both the sectors. In fact concerning individual transportation, ICT can help people to plan travel in a more conscious way providing real time information on traffic congestion or advising the presence of accidents in the routes, improving eco-driving for passenger vehicles giving real-time feedback on miles per gallon. ICT can also smooth traffic installing sensors on traffic lights and road surfaces to manage the road system of a given city or area.

In the other hand ICT can act on commercial transportation in three ways:

- enhancing the supply chain designs
    - determining optimal locations of distribution center using software algorithms
    - maximizing the load analysing packaging type
    - using modes of transport with lower consumptions
- improving delivery implementation
    - avoiding congestion and idle periods with a real-time planning of routes

  - using the empty space on vehicles to carry goods that need to be returned or redistributed

- enabling eco-driving, same solutions adopted for individual transportation

1.3.3 Smart buildings

Within the challenges against GHG emissions, buildings should be a key point to be analysed since they represent the 40% of the entire CO_2 emissions in the atmosphere in the U.S. in the 2007 and this percentage is expected to grow by 48% in 2030. The forecasts in 2020 of the CO_2 emissions reach the value of 2570 MMT of which 1760 represents new construction. This is an interesting datum because it is much more cheaper and easier to build new energy efficient buildings than to work on the efficiency of old buildings.

The ICT-driven potential reduction in 2020 goes from 270 to 360 MMT and can be derived in equal proportion by the design phase and by embedded technologies.

Design sets the initial energy consumption of a building: in this phase simulation and modeling design softwares help to properly choice the building size, to exploit the natural light, to use more efficient material in order to avoid heat-losses,optimize the air flows and to manage the *heating, ventilation and air conditioning systems* (HVAC).

In the other hand technology minimizes energy consumption of building operations with many solutions:

- smart devices able to switch on and off
- smart controls such as thermostats to manage energy consumption
- sensors to turn off lights and devices when a room is empty
- integration and remote control of multiple devices such as HVAC, power, lighting and fire alarm
- smart meters and gateways to connect to smart grids exploiting the opportunities well explained in subsection 1.3.1.

1.3.4 Travel substitution

The extraordinary development of the Internet and of broadband connectivity has created new opportunities in the way people live and work. Cooperation tools and video-conferencing can actually eliminate the need for traveller to mandatory meet in person and there are more and more workers that could work from anywhere at any time but nowadays only a few percentage exploit this opportunity.

Besides the expected 2020 value of 1370 MMT of CO_2 emitted, the need to travel is responsible for additional problems like wasting of time, each worker spend on average 50 minutes to get to the workplace everyday, traffic congestion and high travelling costs.

Today it is possible to get many of this activities *virtual* such as meetings and even to adopt different working solutions and the result is a potential reduction in 2020 of about 100 MMT of CO_2.

The large part of this amount, around 75%, is brought by *flexible work* whose idea is to *bring work to the employee instead of bringing employees to work.* This solution mainly requires three things:

- *broadband* connection, both fixed and mobile, for the workers
- an integrated platform of all the communication tools (i.e. instant messaging, email, video-conference and so on)
- devices (laptops, smart phones) that keep each worker connected from any location

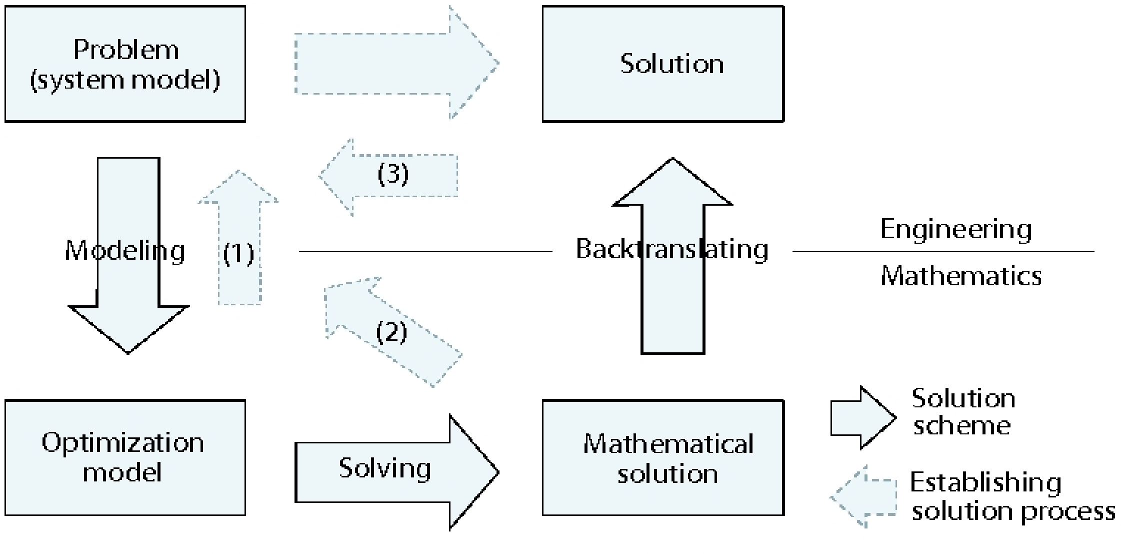
Moreover the remaining part (25% of the potential reduction) is achieved by replacing in-person meetings with remote interaction such as video-conferences. In this case there are strong technology and network requirements to enable efficient communications.

Chapter 2

Planning a wireless network

2.1 Solution-oriented modeling

The exceptional rise of the telecommunication industry has implied the necessity to put more effort on the design of the networks. [49] shows us the importance of *solution-oriented modeling* and even of *mathematical optimization* to perform efficient planning for wireless networks.



Source: *Wireless network design: solution-oriented modeling and mathematical optimization* (A. Eisenblatter, H. Geerd)

Figure 2.1: The problem solving cycle of modern applied mathematics

The mathematical optimization process can be summarized, as shown in figure 2.1, as follows:

1. translation of the real problem into an optimization model

2. resolution of the optimization model
3. translation of the mathematical solution into the real world problem

This approach is very different from the generic *engineering-driven* automatic optimization that puts more emphasis on the description of the system.

Let us now mark out the peculiarities of *system* and *optimization model* in order to show their main differences.

A *system model* is the result of a thorough system analysis using all engineering knowledge available. This study assures a clear comprehension of the problem, what can be obtained, the significance of the parameters and how to evaluate the quality of a solution.

Referring to figure 2.1, a system model is represented by the upper layer of the scheme.

On the other hand the *optimization model* is the lower level of figure 2.1 and its main characteristic is to mark the optimization's purpose as well as the necessary constraints in mathematical terms allowing the use of strong optimization methods to get the solution. It is fundamental, even for computational reasons, to ignore features not implied by the model.

A key point when building an optimization model is thus to decide the desired characteristics of a solution and neglect the others. The two basic requirements for a well done optimization model are:

- efficient computational solution
- applicability of a good solution of the optimization model to the system model

The first forces the model to be as simple as required by the optimization methods we want to use to solve it, the second states that during the optimization model creation the operated simplifications do not affect its suitability for the real world problem.

The backward arrows in figure 2.1 show how the research of an appropriate optimization model is an iterative process that is to say a continuous production of models until finding one that respects the aforementioned fundamental requirements. In particular back arrow (1) occurs when the complexity of the created optimization model needs to be reduced because it is not possible to be solved in an efficient way, back arrow (2) implies that further experiments are required to better identify aspects to be kept in the model and other to be discarded and back arrow (3) shows the necessity, driven by wrong early solutions of the process, to modify the original system model in order to get more effective solutions.

2.2 Mathematical optimization

The optimization models can be classified according to the complexity of the objective function and the constraints.

In the simplest kind of model both objective function and constraints are linear and when the complexity arises it is more and more difficult to find a good solution. This is why the linear models, potentially involving integrality constraints, are among the more widespread: such models are called *mixed integer linear programs* (MILP).

The general form of a MILP is:

$$\min c^T x \tag{2.1}$$

$$\text{s.t.} Ax \geq b \qquad x \in Q^{n_1} \times Z^{n_2}, \tag{2.2}$$

$$\tag{2.3}$$

where b and c are vectors in Q^m and Q^n, A is a $m \times n$ matrix and $n = n_1 + n_2$ with $m, n_1, n_2 \in N_0$. x is the variables n vector which have the first n_1 elements linear while the remaining n_2 must be integer.

MILP are *NP-hard*, that is to say there are no known algorithms with polynomial solving time.

Nevertheless there are very efficient MILP solvers which can find optimal or absolutely good solutions with reasonable computational time, even for large instances. Note that this is not inconsistent with the previous statement because *NP-hardness* means that some instances are hard but does not preclude the possibility of a major fraction of a *NP-hard* problem to be solved in polynomial time.

There are four basic models that can be solved to optimality or close to optimality with a reasonable effort by a MILP solver:

Set covering. Given a family of sets over a common ground set (called *universe*), the task is to choose some of these sets such that the union of the selected elements contains all the components of the *universe*. Usually, the number of selected sets is to be minimized. This model is well suitable for coverage problems.

Facility location. Given a set of facility locations and a set of users who have to be served from the facilities, the problem is to install facilities in the region where there are customers. The average proximity of the facilities to customers is to be minimized. A typical example of facility location problem is cellular network design.

Assignment. In case of bipartite assignment, elements in one set (customers) have to be assigned to elements in another set (facilities) subject to a linear utility function.

Knapsack. Given items of different values and volumes, the task is to find the most valuable set of items that fits in a knapsack of fixed volume. The knapsack problem is the simplest form of an integer linear program since it has one constraint and a linear objective function, all with positive coefficient. If the problem has more than one constraint, it is called *multiple knapsack*. This model well describes the capacity of a cell in wireless network design.

When creating a new model, the closer it is to one of the previous four the more likely it is to get a good solution in a polynomial time.

There are several mathematical modeling languages and among them in our work we used *AMPL* with the aid of the solver *CPLEX*.

2.3 Cellular networks planning

Now it is interesting to understand how the methods described in the previous sections are effectively deployed in real wireless networks. We start with cellular networks presenting two familiar problems:

- *GSM* coverage planning
- *UMTS* network design

In particular we analyze the similarities of these problems with the four benchmark models described before.

2.3.1 *GSM* coverage planning

The standard planning schemes for *GSM* radio networks distinguish coverage planning from capacity issues.

In the first planning phase the locations of the BSs are chosen in order to provide continuous coverage of a given area. In this situation we can directly apply the *set covering* model. The simplest case is that selects locations for BSs all with fixed configurations.

The objective is to design a network that is cost effective subject to the covering constraint of a given area A (in the form of *pixels*). Each BS location i has a cost c_i to deploy a base station on it. We can derive the set C_i of pixels potentially covered by BS i from the propagation data.

This is the standard *set covering* model for the described system:

$$
\begin{aligned}
\min\ & \sum_i c_i x_i & \\
s.t.\ & \sum_{i:p\in C_i} x_i \geq 1 & \forall p \in A \\
& x_i \in \{0,1\} & \forall i
\end{aligned}
$$

where the binary variables x_i states whether location i is used or not.

This model is suitable for almost any digital radio technology.

The second step is to adapt this ideal scenario into a realistic one. Modifications typically concern the antenna configurations, i.e. antenna types, number of sectors, azimuth and tilts per sector.

Moreover we can modify the constraints forcing the service area to be covered to some threshold percentage.

All these variations are enough close to the structure of the *set covering* model to be usually well solvable in practice too.

2.3.2 *UMTS* network design

The commercial use of *UMTS* presents new issues for radio network planning. Only one or two frequency bands are commonly used within a network in *frequency-division duplex* (FDD). Communication links are kept apart with the use of *code division multiple access* (CDMA) techniques and interference is minimized through *power control* methods.

Practically all the features of network performances, namely coverage and capacity planning, rely on the interference condition thus in the planning phase interference has to be seriously considered.

In this situation pure *set covering* models (at most with *knapsack* constraints) can be used only to provide lower bounds on the minimum BSs number to cover a given area. But these models lack in the interference analysis and in its implications on the whole network planning.

It is crucial to deploy a system and subsequently an optimization model that deeply concerns with interference coupling. Recent studies describe the network's state with a planned set of served users by the following simple equation:

$$p = Cp + \eta$$

where p is the vector of received signal strength at the cells, C is the *interference coupling* matrix which displays the mutual interference between couples of users and η is the noise.

2.4 WLAN planning

Wireless LAN based on the protocol 802.11 is a very popular broadband radio access technology. In the *infrastructure mode* it is quite similar to a *micro-cellular* network in which *access points* (APs) act as BSs.

The peculiarity of *WiFi* technology is the radio access protocol which has the following features:

- no difference between *uplink* and *downlink*
- each station has to compete for the wireless medium using a *carrier sense multiple access* (CSMA) protocol with a random backoff time
- no communication is possible between two users if there are no stations within the reception range

Moreover it is possible to reduce contention assigning different frequencies to APs (the maximum number of channels is 13, of which there are only 3 not overlapping as portrayed in figure 2.3).

Interference has to be taken into account in the planning phase of this kind of wireless network and two main points have to be considered for the APs: position and channel assignment.

The first item is more suitable for models of *set covering* type. But in WLANs the data rate strictly depends on the received signal strength as shown in figure 2.2 and in particular for IEEE 802.11g it ranges from 1 to $54MB/s$. This behaviour can be efficiently considered with the facility location models.

If the objective is to maximize the mean throughput per pixel j with a predetermined number k of APs we can use the following facility location formulation:

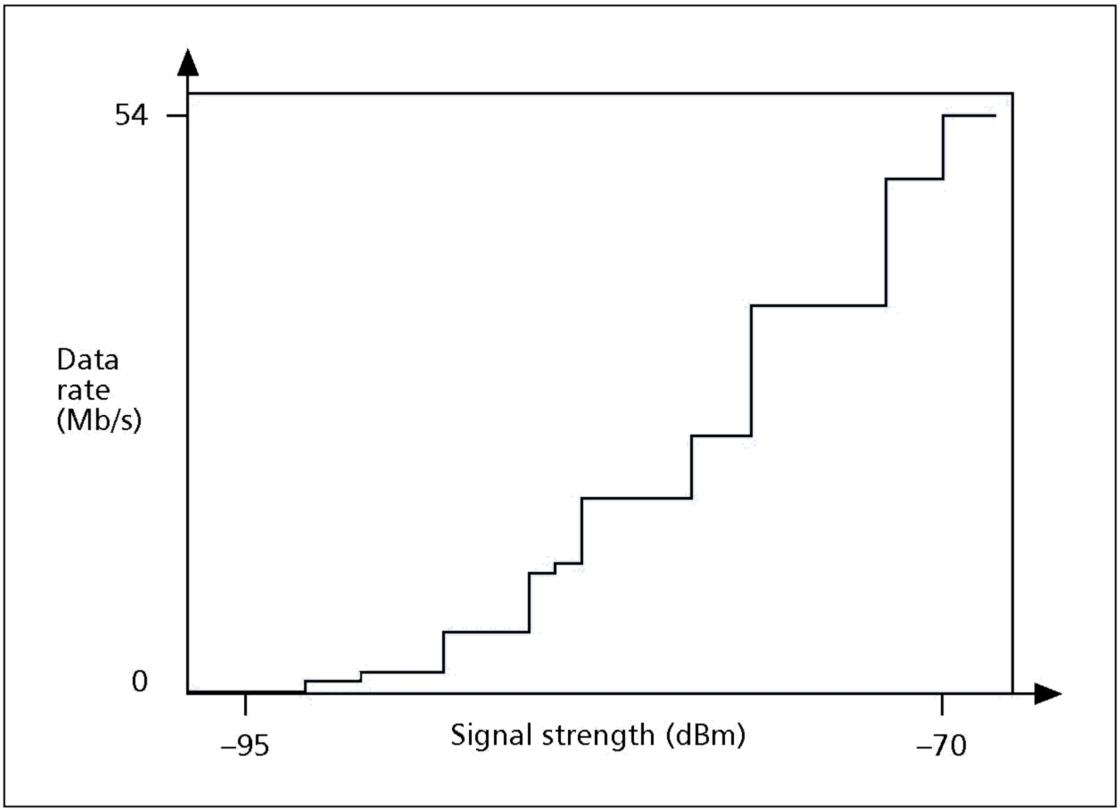


Figure 2.2: Data rates used in IEEE 802.11g WLANs. The values correspond to the objective function coefficients r_{aj} in the facility location model [49]

$$
\begin{aligned}
\max \ & \sum_{a,j} r_{a,j} x_{a,j} & \\
\text{s.t. } & x_{aj} \le z_a & \forall a, j \\
& \sum_{a} x_{aj} = 1 & \forall j \\
& \sum_{a} z_a \le k & \\
& z_{aj}, x_{aj} \in \{0,1\} & \forall a, j.
\end{aligned}
$$

The binary set of variables z_i states whether AP location i is selected while x_{aj} implies that AP a serves pixel j.

As expressed in figure 2.2, r_{aj} is the maximum data rate provided to pixel j by AP a and it is used as a coefficient in the objective function.

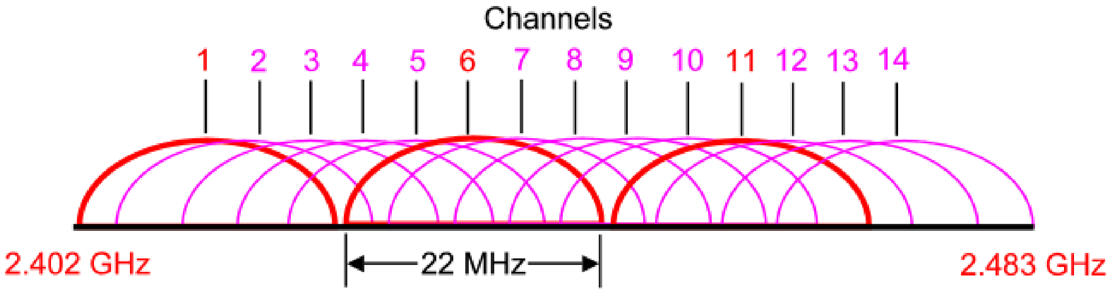


Figure 2.3: Three non-overlapping channel for *WiFi* 802.11g

In the aforementioned model CSMA protocol is usually not specifically taken into account in order to keep the problem simple and easily solvable. Nevertheless the integration of CSMA's issues is possible with some modifications.

[40] proposed the addition to the standard *set covering* model of a new hyperbolic objective function to consider the channel's contention. The presented problem, named *Planning Capacity with hyperbolic formulation* (PCH), has the following formulation:

$$\begin{aligned}
&\max \sum_{i\in I} \frac{1}{\sum_{h\in I} y_{ih}} && \\
&\text{s.t.} \sum_{j} a_{ij}x_j \geq 1 && \forall i \in I \\
&\quad a_{ij}a_{hj}x_j \leq y_{ih} && \forall j \in J, \forall h, i \in I \\
&\quad x_j \in \{0,1\} && \forall j \in J \\
&\quad y_{ih} \geq 0 && \forall h, i \in I
\end{aligned}$$

where the additional variable y_{ij} states whether users i and j are covered by the same BS.

The algorithm to assign channels is quite similar to the frequency assignment in *GSM* but with only three channels. Appropriate models perform this behaviour and [39] shows that medium sized instances are solved in few minutes with standard softwares.

Chapter 3

Green Networking

The literature concerning *green networking* is quite large, heterogeneous and very recent since the great involvement in the theme of energy saving belong to the last decade.

In what follows, we present a survey on the basic techniques and algorithm used in the world of telecommunication to save energy.

We'll start with wired networks and in particular the Internet then we'll shift attention to the wireless world focusing on cellular and WLAN networks.

3.1 Internet

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 [15].

The aforementioned paper was one of the first focusing on the great energy inefficiency of the Internet and presented alarming results based on the exceptional expected widespread of this network and consequently the increase in energy consumption. It is estimated that the Internet infrastructure alone is responsible for about 1% of overall electricity of broadband provided countries [41, 42] and this percentage arises to % if we consider all the related equipments (servers, data centers and user's devices).

Moreover [15] denoted the necessity of energy conservation especially in most developing countries where energy is very limited and not well provided. Furthermore a new management of networks for energy saving purposes results in the abatement of operational expenditures (OPEX) and of capital expenditures (CAPEX) costs.

Good overviews of the research on green networking and methodological classifications are given in [24, 25] where different methods adopted in the literature for both wired and wireless networks are surveyed.

3.2 Sources of wastes and key points

One of the major sources of energy wastes deals with network equipments. They work in three possible ways:

- *Active/Busy*, the machine is powered on and it is used
- *Idle*, the machine is powered on along with all its functionalities but it is not used
- *Sleep*, the machine is not used and only a little subset of its components is powered on

As a matter of fact the *idle*'s consumption is almost the same of *active* mode while the consumption of *sleep mode* is considerably lower.

Moreover it is interesting to analyse the implications of figures 3.1 and 3.2, that are the representations of the consumption of routers (data from [32]) respectively provided and not with wireless functions in both cases with and without traffic. We can see that there is only a small difference between the two situations.

Another source of inefficiency is related to the backwardness of the equipments. Figure 3.3 is the graph of power consumption and ratio frequency over consumption (MHz/W) for seven different families of CPU made by *Intel*. We can note how the ratio increases even though the consumption grows in absolute terms.

Nevertheless the ratio of performance versus power decreases with the increase of the capacity and of the maximum throughput achievable by the router. The fact suggests that bigger devices are generally more power efficient.

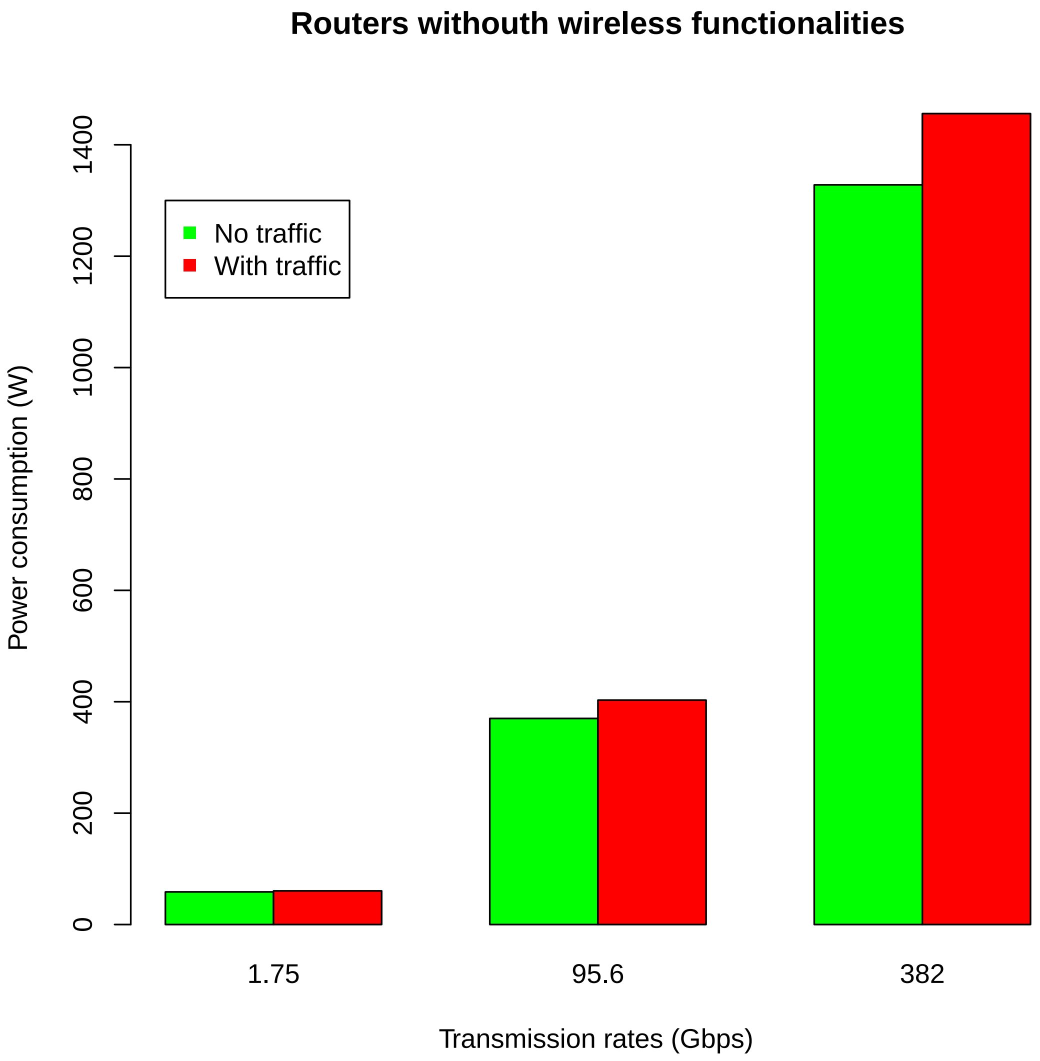


Figure 3.1: Power consumption of routers without wireless functionalities in both cases with and without traffic. Data source [32]

In addition to the factors that affects the energy consumption of the Internet we can mention the packets' length and in particular figure 3.4 shows, at a constant traffic rate, how the routers' consumption arises with the length of the packets.

[24] classified all the approaches adopted to save energy within Internet into three wide groups according to the utilized technique:

- partition of the network resources for a more efficient utilization (*virtualization*)

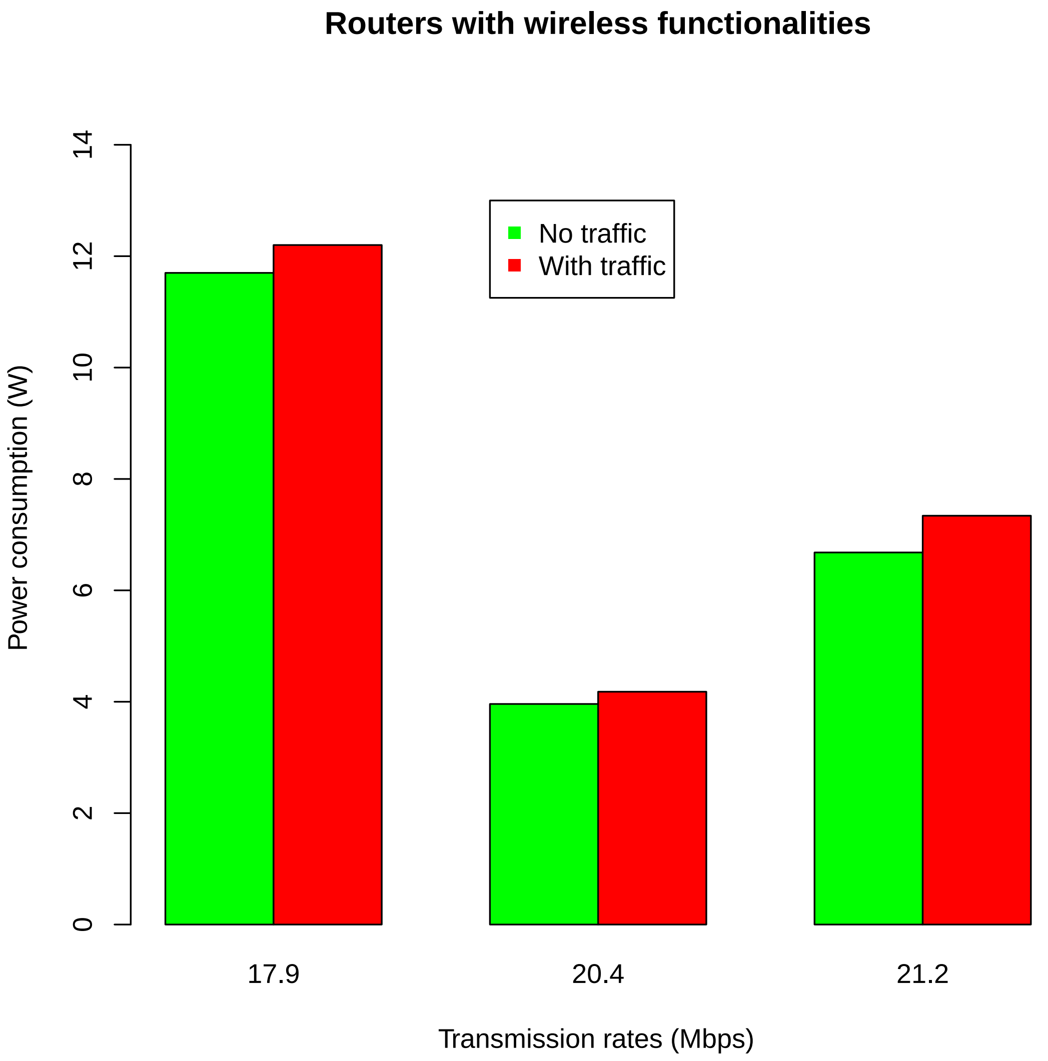


Figure 3.2: Power consumption of routers with wireless functionalities in both cases with and without traffic. Data source [32]

- power management and network design
- deployment of new smarter technologies

3.2.1 Virtualization

The idea of using one server to host only one application has been deeply utilized over years by service providers and ICT companies but the latest studies of the sector have demonstrated that this way of allocation of the resources is quite inefficient and

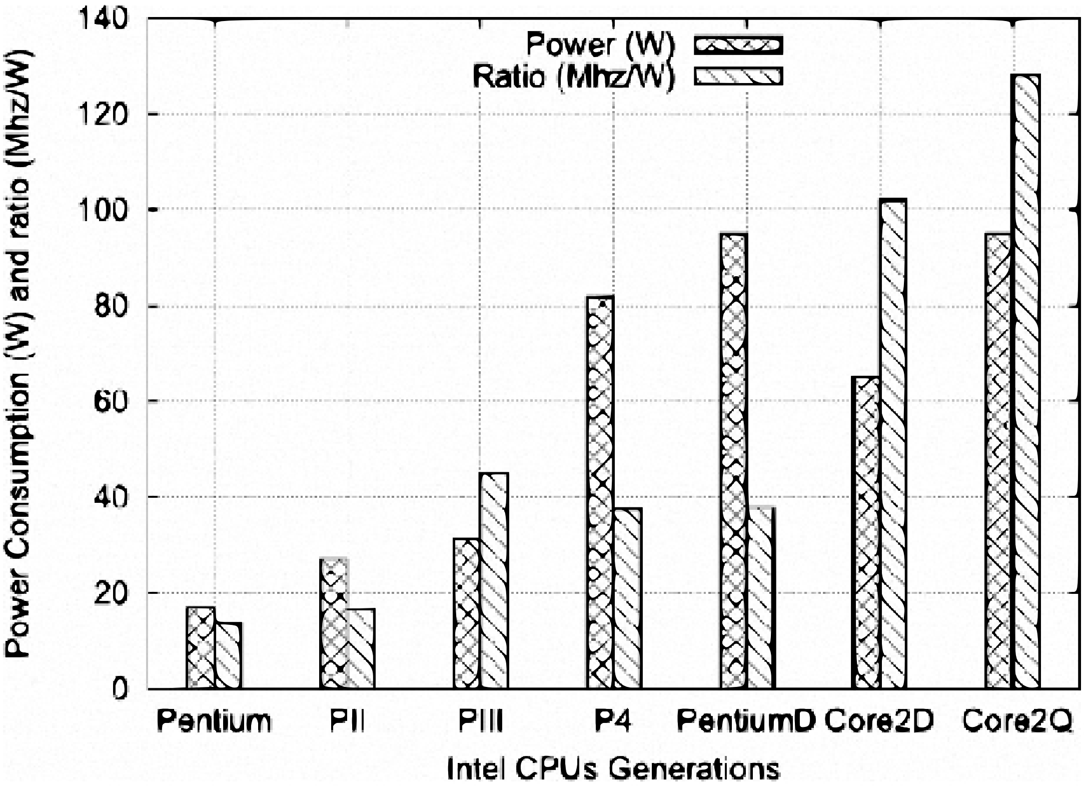


Figure 3.3: Power consumption of different Intel CPU generations. Data source [33]

a new idea is acquiring more and more importance and spread in the world of ICT, *virtualization.*

It consists in the combination and consolidation of different kinds of applications in the same server and launching them in a smaller number of servers. Generally speaking one physical server is subdivided into multiple virtual servers.

There are mainly four types of *virtualization*:

full virtualization: (also referred to as *hardware emulation*) the application is run with no changes, server hardware is hidden from the guest OS and a special machine, *virtual machine monitor* (VMM) manage the coordination between OS and hardware within the server. The advantage is that the application can work with server with no modifications thanks to VMM

paravirtualization: requires changes to the virtualized operating system to allow the coordination of the VMM with the hypervisor and to reduce the number

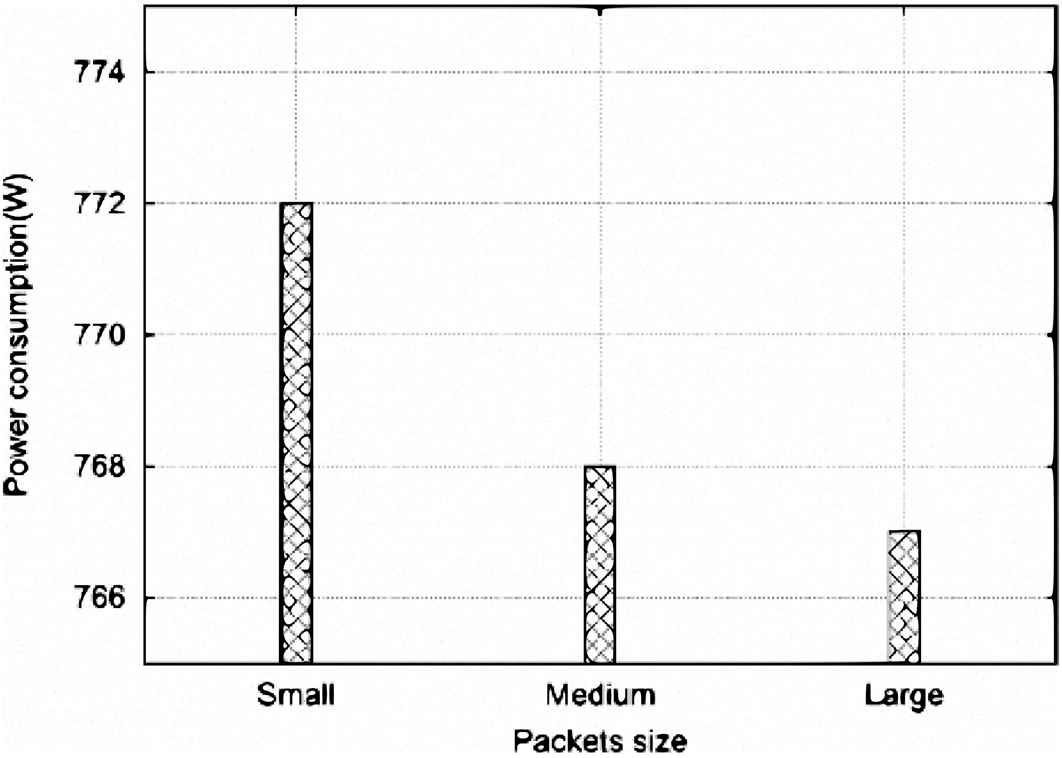


Figure 3.4: Cisco Catalyst 2970 LAN switch power consumption per link for different link rates. Data source [34].

of privileged instructions that decrease the performance of the system. Servers that implement paravirtualization are more performing but less simple to use, in fact it is necessary to modify the OS to be hypervisor-compatible

OS virtualization: does not rely on a hypervisor. The operating system is modified to securely divide, within a single machine, multiple instances, usually referred to as *virtual private servers* (VPS). The lack in hypervisors results in a enhancement of the performances with the negative consequence that all VPSs share a single kernel (low stability and resistance to eventual crashes) [43]

native virtualization: based on hardware's support. Multiple unmodified OSs running alongside on the same server. It is not an *emulation* of a processor like in the *full virtualization* but all OSs run on the host server directly.

3.2.2 Power management and network design

Energy consumption was often neglected from design issues, the parameters considered were mainly cost, reliability, QoS and so on but in the very last years, as written so far, energy saving has become a fundamental issue that could not be ignored anymore.

The very fast expansion of the Internet and consequently of the energy consumption is a matter to be carefully considered: one possible approach is a smarter management of the power, another relies on deep analysis of the architecture and on the way networks are expanded or redesigned.

Power management is mainly based on two concepts, the idea of switching off unnecessary elements, which will be developed in the rest of our work, the idea of *sleeping*, that is to say putting into *sleep state idle* devices and the idea to dimension to capacity of links according to the workload.

[20] analysed the theme of *sleeping* and identified two possible approaches:

timer-driven: devices start and stop *sleeping* at predetermined times controlled by a clock

wake-on-arrival (WoA): elements wake up only when they are necessary

In the first case, elements specify the time to wake up before entering to sleep and all packets arrived meanwhile are definitely lost. The advantage of this solution is the lower hardware requirement for the devices. While in the second case, elements wake up in an automatic way on sensing incoming traffic.

[44] proposed a selective *wake-up* mechanism that reduced the idle listening power through the use of two RF modules: one for the wake-up mechanism and one for data communication. The mechanism is made up of two steps: first the *radio waves detector* (the only active part when in sleep state) wakes the *ID matching circuit* up when receiving a packet and, if it is a *wake packet*, the data communication module finally wakes and the transmission can start.

One of the problems of this technology is with the *broadcast* transmitting, that characterizes the main part of wireless transmissions, because a *wake packet* can wake up several AP so we need a distributed algorithm to avoid false positives events. Furthermore the wake-up mechanism has fundamental hardware requirements without which cannot be used.

Another main problem is the underutilization of links, in particular the offered capacity is often much more higher the the actual load flowing on links. One possible approach is to dynamically adapt the power, and consequently the channel transmission rate, according to the traffic demand. This process is usually referred to as *adaptive link layer* (ALR).

This technique increases the utilization of links and the energy efficiency of the network. The main requirement is the coordination among nodes during transitions from and to low power consumption state. These transitions may cause data losses or increased delays.

As well as these techniques, possible solutions to energy saving can be derived from a thorough analysis of the system followed by a redesign in order to eliminate eventual bottleneck or sources of energy wastes and inefficiencies.

A lot of networks are designed to assure a high level of reliability and robustness, but this results in too many redundant equipments and energy wastes. [45] presented a trade-off between resilience and power expenditures.

3.2.3 New technologies

The adoption of new and smarter technologies when designing and producing new devices really affects their performance, and in particular the energy consumption. Two of the most effective technologies in reducing the energy consumption of machines and networks are:

Optical technology as [46] and many following papers suggested, the introduction of optical technology like *IP over WDM* improved both bandwidth and energy efficiency

Advanced CMOS technology and superconductors the reduction of the size of the gates, the building blocks of chips, involves in a decrease of the per-gate energy consumption. $45 - nm$ technology implies a reduction of 40% of the energy consumption of chips compared to $65nm$, as shown in [47, 48].

Most of the concepts expressed so far in this chapter concern with both wired and wireless networks, in what follows, we focus on wireless networks only.

3.3 Wireless networks

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 [26], 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 [15] 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* 802.11*b*). 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.

3.3.1 Cellular network

Concerning cellular access networks, [2] deployed the idea of switching off some nodes. In particular it considered a system with the following features:

- a given physical network topology, comprising routers and wireless links, with known capacity and maximum utilization

- the average traffic matrix (source, destination and load)
- the power consumption at each link and node

In such a system the authors of the aforementioned paper aimed at finding a subset of routers and links to power on so that the power consumption is minimized subject to *flow conservation* and *maximum utilization* constraints. Two different heuristics were presented, one *node-oriented* and the other *link-oriented*. The former is more difficult to implement but has an higher impact on the objective function. At the end the two approaches were combined showing how is it possible to reduce energy consumption switching off nodes and links.

One limit of the previous work was to not consider traffic variations over time but to dimension cellular systems for peak traffic conditions. [13] introduced the variability of the traffic demands at each cell and proposed a novel energy saving approach based on the dimensioning of the resources according to the load. The percentage of energy saved depends on the congestion level of the networks so that low traffic periods result in a great amount of saving. He studied different traffic patterns reaching values of saving of about $25 - 30\%$.

Another energy management study is provided by [12] where it is shown that the on-off strategy for *UMTS* BS is feasible in urban areas. It considered two different scenarios and measured the energy saved by switching *Node B* in both cases obtaining a percentage of energy saving that ranges from 25% to 50%.

[14] considered a random traffic distribution and dynamically minimized the number of active BSs to meet the traffic variations in both space and time through. It presented two algorithms to manage the powering on and off of the BSs: a *centralized greedy* one more suitable for low traffic periods and a *decentralized* to relax the information requirement. The latter is based on an utility function which can locally be calculated at the BS. This utility function give higher weights to BSs with major workload. The value of this utility function can be transmitted broadcast through a dedicated signalling channel.

3.3.2 WLAN

In WLANs, we mention the work of [37] that presented strategies based on the resource on-demand (RoD) concept in the field of high density WLAN with redundant layers of AP.

In particular it focused on enterprise WLAN: the number of enterprises involved in this kind of network is growing exponentially every year and the investing budget has been spent to design very dense WLAN in order to provide connectivity even in heavy load conditions. But such a situation represent only a few percentage of a network life and for the remaining part of the day this is a bad allocation of resources and need to be adequately managed in order to avoid energy wastes.

The idea of the paper is to vary the number of active AP according to the traffic demand of users within the network through a kind of resource on-demand algorithm.

There are two kinds of RoD methods:

Demand-driven: WLAN can switch on and off nodes based on the user demand at a given time. Such a method provides an optimal set of AP to be active in order to satisfy the traffic demand but has strong requirements in term of APs' coordination and reconfiguration and computation time and resources. The advantages are high energy savings while satisfying end-user performance.

Schedule-driven: APs' activity times are scheduled on the basis of previous studies and of administrators' experience. They have very low OH costs but they fail in providing the right level of connectivity when the traffic condition varies significantly from the scheduled one. It is best suitable for high predictable scenarios.

The proposed RoD strategy is of *demand-driven* type and has the following requirements:

coverage guarantee to all users, in particular to a predetermined set of *test points* (TP). At each time interval all TPs must be covered by at least one BS

keep QoS not depending on the networks load. This point is strictly related to the WLAN topology. The ideal objective is to provide the same performance of the networks with all powered on devices.

avoid frequent APs' reconfigurations which causes delay and traffic interruptions negatively influencing the performance.

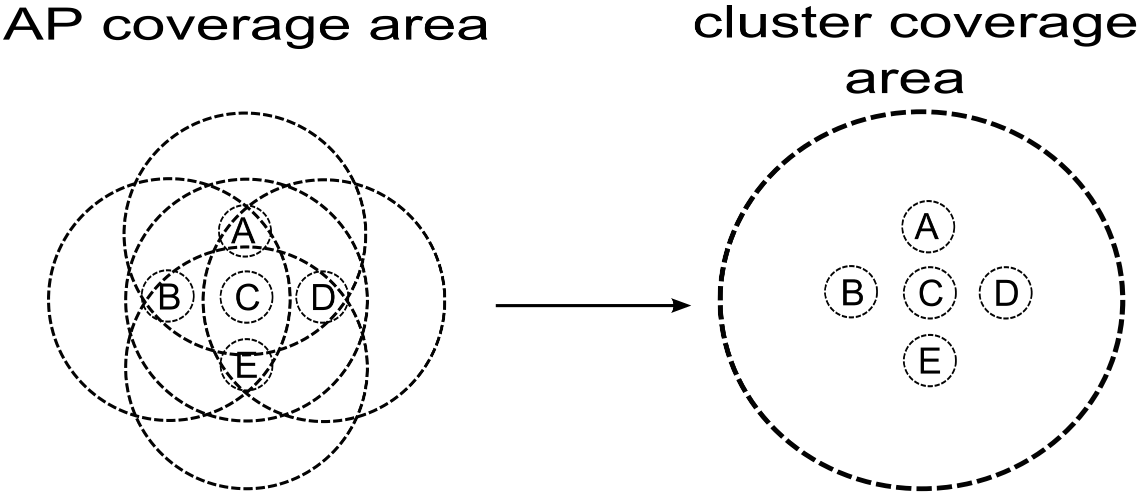


Figure 3.5: Cluster formation

The strategy is called SEAR (*Survey, Estimate, Adapt, Repeat*) and implies the following steps:

Green clustering division of the set of APs in clusters each one with a *leading* device. The basic assumption is that each AP in the same cluster covers the same region (see figure 3.5)

Demand estimation evaluation of traffic demand and other topology parameters based upon the sensing of the APs channel utilization. This *sniffing* operation is assumed to not affect the performance of each device

Topology management the actual phase of powering on and off APs according to the information brought by the previous steps

User management re-association of the clients according to the new topology

Even though our analysed system (as shown in chapter 4) is very different, this work has been a good source of inspiration for us, especially for the idea to let the consumption varies according to the load avoiding the underemployments of the resource.

[9] proposed an analytical model to assess the effectiveness of RoD strategies in a system that is very similar to the one considered in the previous analysed paper [37]. In particular the similarities are the kind of WLAN, the clustering features and RoD concept. The main difference is that [9] presented a rigorous mathematical model based on *Markov chains* and on *Poisson distribution* of arrives.

This simple mathematical framework is an important feature for the model since it will permit the extension to more realistic user behaviours. The numerical results presented are very interesting: the power saving reaches the value of 87% during the low traffic periods and decrease to 10% in heavy load conditions. The saving is computed with respect to the case with all APs powered on.

A very interesting feature of this model, that influenced our work, is the analysis of the relation between the energy consumption and the volume of traffic.

[11] shows management strategies for energy savings in solar powered 802.11 wireless MESH networks.

The differences of our work with the papers mentioned above is that the latter 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.

Chapter 4

System model and problem description

In this chapter, 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.

4.1 Description of the system

The WMN architecture such as the one presented in Figure 4.1 is made up of fixed and mobile elements, namely Mesh Routers (MR) and Mesh Users (MU). MRs 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 MAPs or MRs. In our networks' *distribution system* MRs and MAPs 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

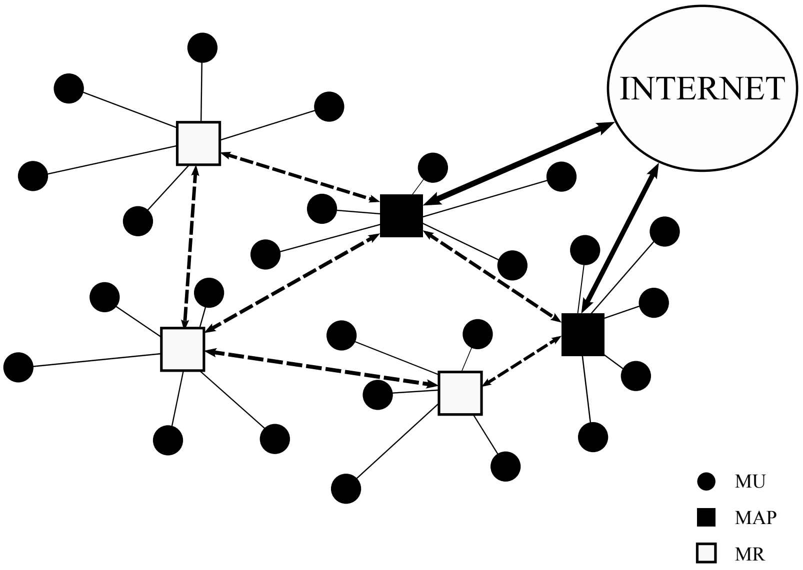


Figure 4.1: Architecture of the network analysed

removed but it can be minimized installing directive antennas and adopting a smart frequency assignment algorithm as suggested in [27]. 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 MRs 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 MUs 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 6.3.

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 4.1: Day division in time intervals and related level of congestion

4.2 Traffic profiles

In [28] and [29] 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 [29] and [28]. The results are presented in Table 4.1.

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.

4.3 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) [30].

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 [31] 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 MRs or MAPs, 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:

$$\min \sum_{j \in S} (c_j z_{jt} + p_j w_{jN}) \tag{4.1}$$

$$s.t. \sum_{j \in S} x_{ij} = 1 \qquad \forall i \in I, \tag{4.2}$$

$$x_{ij} \leqslant z_j a_{ij} \qquad \forall i \in I \forall j \in S, \tag{4.3}$$

$$\begin{aligned} &\sum_{l \in S} (f_{lj} - f_{jl}) + \\ &\quad + \sum_{i \in I} d_i x_{ij} = f_{jN} \end{aligned} \qquad \forall j \in S, \tag{4.4}$$

$$f_{lj} - f_{jl} \leqslant u_{jl} y_{jl} \qquad \forall j, l \in S, \tag{4.5}$$

$$\sum_{i \in I} d_i x_{ij} \leqslant v_j \qquad \forall j \in S, \tag{4.6}$$

$$f_{jN} \leqslant M w_{jN} \qquad \forall j \in S, \tag{4.7}$$

$$y_{jl} \leqslant z_j, y_{jl} \leqslant z_l \qquad \forall j, l \in S, \tag{4.8}$$

$$y_{jl} \leqslant b_{jl} \qquad \forall j, l \in S, \tag{4.9}$$

$$\sum_{h=l+1}^{l_i} x_{ij_h^{(i)}} + z_{j_l^{(i)}} \leqslant 1 \qquad \forall l = 1, ..., L_i - 1, \forall i \in I, \tag{4.10}$$

$$x_{ij}, z_j, y_{jl}, w_{jN} \in \{0, 1\} \qquad \forall i \in I, \forall j, l \in S. \tag{4.11}$$

Objective function (4.1) 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. (4.2) forces each **TP** to be assigned to one active **CS** that covers it (see (4.3)). (4.4) is a classical flow balance set of equations while (4.5),(4.6) and (4.7) are sets of capacity constraints for, respectively, links, routers and gateways. A wireless link between two nodes exists only if they are both active (4.8) and neighbour (4.9). (4.10) imposes the assignment of a **TP** to the nearest active BS while (4.11) 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.

Chapter 5

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.

5.1 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 MRs or MAPs
$G \subseteq S$	the subset of BS that are MAPs (gateways)
$J_h^{(i)}$	the subset of BSs covering **TP** i ordered by decreasing received power where h is the index of position inside the set

Input parameters:

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

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

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

d_{it}	traffic request of **TP** i at time t,
u_{jl}	capacity of the link between BSs 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:

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

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

f_{jlt}	flow between BSs 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

$$\sum_{j \in S} \sum_{t \in T} z_{jt} \xi_j \Delta T \tag{5.1}$$

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 (5.1).

Assigment constraints

There are two type of assignment constraints. (5.2) imposes that at each time interval every **TP** is assigned to a BS and (5.3) 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.

$$\sum_{j \in S} x_{ijt} = 1 \qquad \forall i \in I, \forall t \in T \tag{5.2}$$

$$x_{ijt} \leqslant z_{jt} a_{ij} \qquad \forall i \in I, \forall j \in S, \forall t \in T \tag{5.3}$$

Flow conservation constraints

$$\begin{aligned} &\sum_{l \in S} (f_{ljt} - f_{jlt}) + \\ &\quad + \sum_{i \in I} d_{it} x_{ijt} = f_{j0t} \qquad \forall j \in S, \forall t \in T \end{aligned} \tag{5.4}$$

(5.4) 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 ($\sum_{i \in I} d_{it} x_{ijt}$) is the traffic supply of the device to its TPs. Finally, the last term f_{j0t} represents the flow between the MAPs and the Internet, considered as special node 0.

Capacity constraints

There are several types of capacity constraints. Constraints (5.5) insure that the capacity of each node is respected whereas (5.6) refer to the capactiy of the link. (5.7), on the other hand, imply that the capacity of the Internet access of each MAPs must be m.

$$\sum_{i \in I} d_{it} x_{ijt} \leqslant v_j \qquad \forall j \in S, \forall t \in T \tag{5.5}$$

$$f_{ljt} + f_{jlt} \leqslant u_{jl} b_{jl} z_{jt} \qquad \forall j, l \in S, \forall t \in T \tag{5.6}$$

$$f_{j0t} \leqslant m \qquad \forall j \in G \subseteq S, \forall t \in T \tag{5.7}$$

Best assignment constraints

$$\sum_{h=l+1}^{l_i} x_{iJ_h^{(i)}t} + z_{J_l^{(i)}t} \leqslant 1 \qquad \forall l = 1, ..., L_i - 1, \quad \forall i \in I, \forall t \in T \tag{5.8}$$

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.

$$x_{ijt}, z_{jt} \in \{0, 1\} \qquad \forall i \in I, \forall j, l \in S, \forall t \in T \tag{5.9}$$

Summarizing model $P1$ can be presented as follows:

$$\begin{gathered} \min \quad (5.1) \\ \text{s.t. } (5.2) \text{ to } (5.9). \end{gathered}$$

5.2 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 (5.2):

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

This set of constraints imposes that every **TP** must be assigned to one and only one BS and, since (5.3) 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 (5.2 and 5.3) are relaxed and replaced by the following:

$$\sum_{j\in S} x_{ijt} = h_{it} \qquad \forall i \in I, \forall t \in T \tag{5.10}$$

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

$$\begin{aligned} \text{min} \quad & (5.1) \\ \text{s.t.} \quad & (5.4) \text{ to } (5.10). \end{aligned}$$

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.

5.3 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 chapter 7.

Chapter 6

Resolution approach

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.

6.1 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 BSs to place;
- the architecture, in particular the placement of all devices according to certain controls;
- specific values of the technology used such as access capacity of the BSs, 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.

6.2 Instance generator

6.2.1 Architecture of the application

The model presented in chapter 5 is linear and can be optimized with a linear programming software like AMPL with the help of the CPLEX solver. We need two logically different files to use AMPL: a file with the extension *.mod*, with the declaration of all the parameters and variables, the description of the objective functions and the list of the constraints the problem is subject to, and a file *.dat* with the values of all the declared parameters. Starting from the aforementioned mathematical programming model we can easily translate to AMPL programming language building up the file *.mod*.

The issue is now to find realistic values for data. The trade off is between choosing a network with an optimized design and using a randomly generated WMN. We've chosen, as written in section 6.1, the second way to give an universal value to the results of the optimization and also to let it be applicable to real existent networks.

For this reason we developed a software that at every run creates a WMN with the features well explained before and writes its parameters' values in a file *.dat*. The rest of the section shows the main features of the IG software.

Analysing figure 6.1 we will discuss each step of the application using the counters, assigned to all of them, in round brackets. IG takes several input values, as specified in subsection 6.1, the most important are the number of CSs and TPs (step 2). Then it first generates the CS set (step 3) according to a certain number of controls (step 4), presented in 6.2.2, added to ensure the aforementioned features.

Then there is the choice of gateways (step 5) and in particular MAPs and MRs are in a ratio of one to fourteen, so there is an access point every fifteen CSs. That completes the procedure of creation CS (step 6).

While the TPs are generated one by one according to another series of constraint (subsection 6.2.2) so we use an integer variable i initially set equal to one (step 7) and then it is incremented (step 10) every time a TP is generated (step 8) keeping to all the constraints (step 9).

After generating the desired number of TPs (step 11) IG generates a traffic profile (step 12). The process of creation of the traffic matrix is discussed in section 5.3.

At this point the instance is created and IG has only to write the file *energy.dat* related to the WMN generated.

6.2.2 Controls added to the random generation

As shown in figure 6.1, the application IG does not create a purely random WMN but the network created is subject to this series of controls:

- control A (figure 6.1 - step 4)
  - the *Backbone network*, the one formed by MRs and MAPs, must be totally connected, that is to say that any given node can communicate throw multi-hop links with all other nodes;
  - every CS must have at least r neighbours;
  - the distance between any two CSs must be greater than a value κ
- control B (figure 6.1 - step 9)
  - every TP must be covered by at least s BSs;

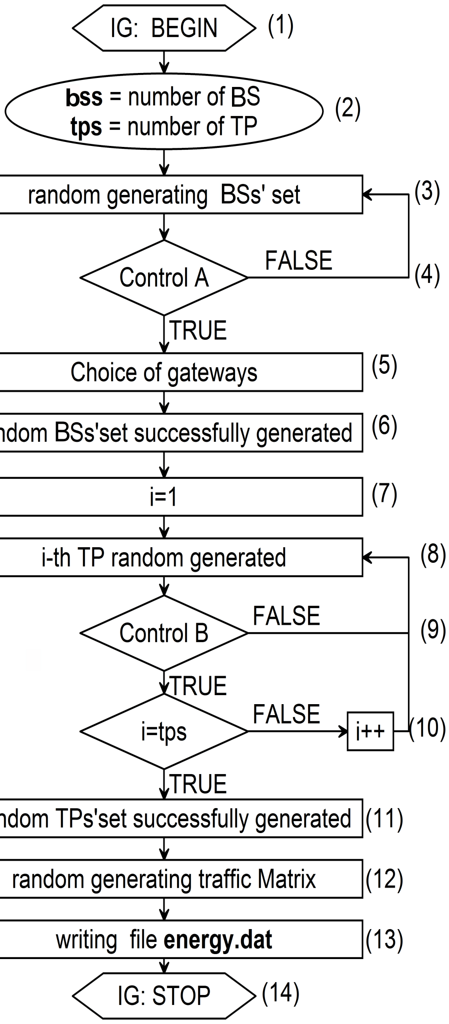


Figure 6.1: Simplified flow chart of the application *Instance generator*

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

Table 6.1: Types of WMN used in our optimization analysis

  - feasibility control[1] , each CS can be the closer device for a restricted set of TP of dimension $Q = \frac{\omega}{v}$ where ω is the maximum value of traffic that a MU can request and v is the access capacity (section 5.1)

We have also defined a minimum distance that must be kept between each couple of CSs in order to create a more realistic network and to avoid cases with too close devices.

6.3 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 MRs or MAPs;
- $R_2 = 250$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 6.1. 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.

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[1] The reason why we insert this control is strictly related to constraint 5.8 that forces a TP to be assigned to the nearest active CS. So we dimension our network in the worst case of all user active and demanding for the maximum traffic.

Chapter 7

Numerical results

7.1 Parameters of analysis

We have generated 150 instances for each kind of WMN presented in Table 6.1 and all the mean results over the 150 instances will be shown in Table 7.1. 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 the value of objective function (5.1); 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:

- 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 TPs are active and demand the maximum value of traffic. It is then clear that while β depends

	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 7.1: Numerical results of the optimization process

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.

7.2 Energy performances

From Table 7.1 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 BSs is realistic. There are no unnecessary devices installed

	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 7.2: Number of active BSs for the small **WMNs**

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 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.

	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 7.3: Number of active BSs for the medium **WMNs**

	Large 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	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											
			$P1$						$\underline{P1}$					
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 7.4: Number of active BSs for the large **WMNs**

A more detailed view of the energy management features and its relationships with network topology can be appreciated by inspecting Tables 7.2, 7.3 and 7.4. 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 **MAP**s) is equal to the initial problem. We can see that, with respect to the BS of the small network (see Table 7.2) 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 BSs shut down. For the large network (Table 7.4), the situation occurs in just one interval, for ($t = 4$), also for the busy case. However, for the medium size network (see Table 7.3),no interval or case, among the 150 instances produced with different demand levels needed the maximum number of base stations.

Moreover we can see that the minimum percentage of active BS reaches very interesting values. For the small instances we have 43.75% of the maximum (7 stations over 16). For the medium instances we have 35% (14 stations over 40) for normal traffic and 37.5% (15 over 40) for busy traffic. For the large instances we get 50% (32 over 64) for both traffic profiles. We can also note that the maximum values of active BSs are in almost all time intervals considerably lower in comparison with the case without optimization. For example, among all the medium WMNs, all the instances have in the first three intervals a maximum of 19 BS active over a total number of 40.

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.

7.3 Network topology

To portray the network topologies found from the optimization model, we displayed an instance network for each size (figure 7.1 for the small, figure 7.2 for the medium and figure 7.3 for the large).

Each figure is made up of 5 sub-figures displaying the same network in five different cases:

(a) is the wireless *distribution system* with all BSs active (without having used the optimization process)

(b), (c) represent the active BSs in the given WMN, after applying the optimization model $P1$, at time intervals 2 and 4, that correspond, respectively, to low demand and peak hours

(d), (e) represent the active BSs in the given WMN, after applying the relaxed optimization model $\underline{P1}$, at time intervals 2 and 4

These figures reinforce the considerations made in section 7.2. Figures (b) and (c) give a visual impact of how many BSs we can switch off in the low traffic period while guaranteeing the covering of all the TPs and keeping the connectivity for the whole network. It can be seen that in the large network, shown in figure 7.3-b and 7.3-c, 36 (out of 64) BSs are active in the second time interval whereas 62 are active for the fourth. It can also be appreciated that 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.

Comparing figures (b) and (d) we can see the additional energy saving that we can achieve relaxing the covering constraints (problem $\underline{P1}$). If we consider the peak traffic periods in the two problems (figures (c) for $P1$ and (e) for $\underline{P1}$) we can note that the situation, concerning the number of active BSs, is almost the same: in fact in heavy load conditions the covering constraints are shadowed by the capacity ones.

7.4 Energy profiles

In Figures 7.4, 7.5 and 7.6 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.

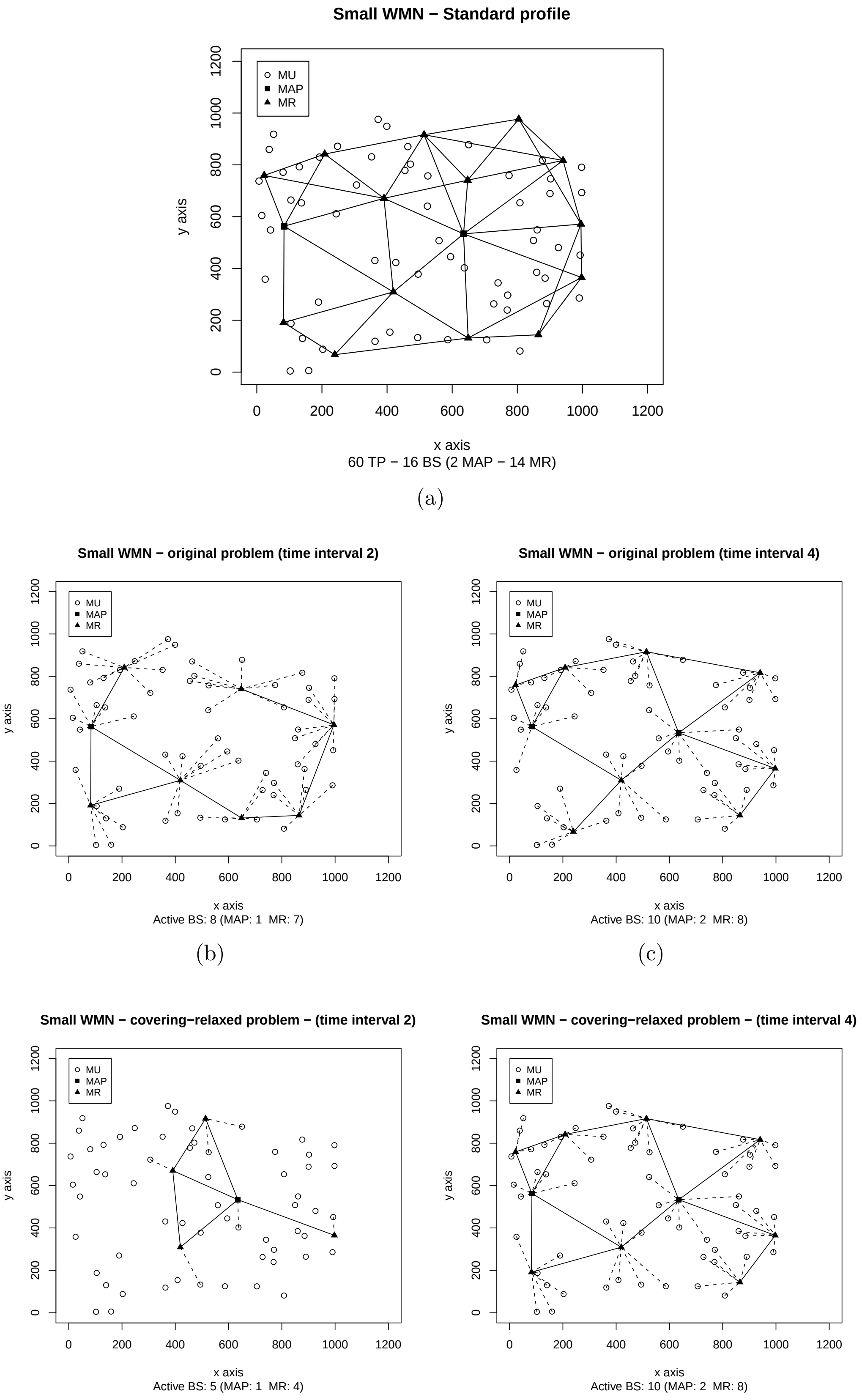
In all the cases the optimization model produces significant energy savings with respect to the full traffic problem. We also observe that the variance of those savings is larger for the busier profiles.

The relationship in energy savings are clearer when the saving percentage α is portrayed for each interval considered, such as in Figures 7.7, 7.8 and 7.9 where the cases respectively for small, medium and large instances are 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 7.9 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 WMNs. Furthermore Figure 7.9 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 TPs 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 BSs even when there is no-traffic.

Our final results are portrayed in Figures 7.10, 7.11 and 7.12 that show the curve of consumption versus different levels of traffic for the two different traffic profiles in small, medium and large WMN. 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 $P1$ 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.

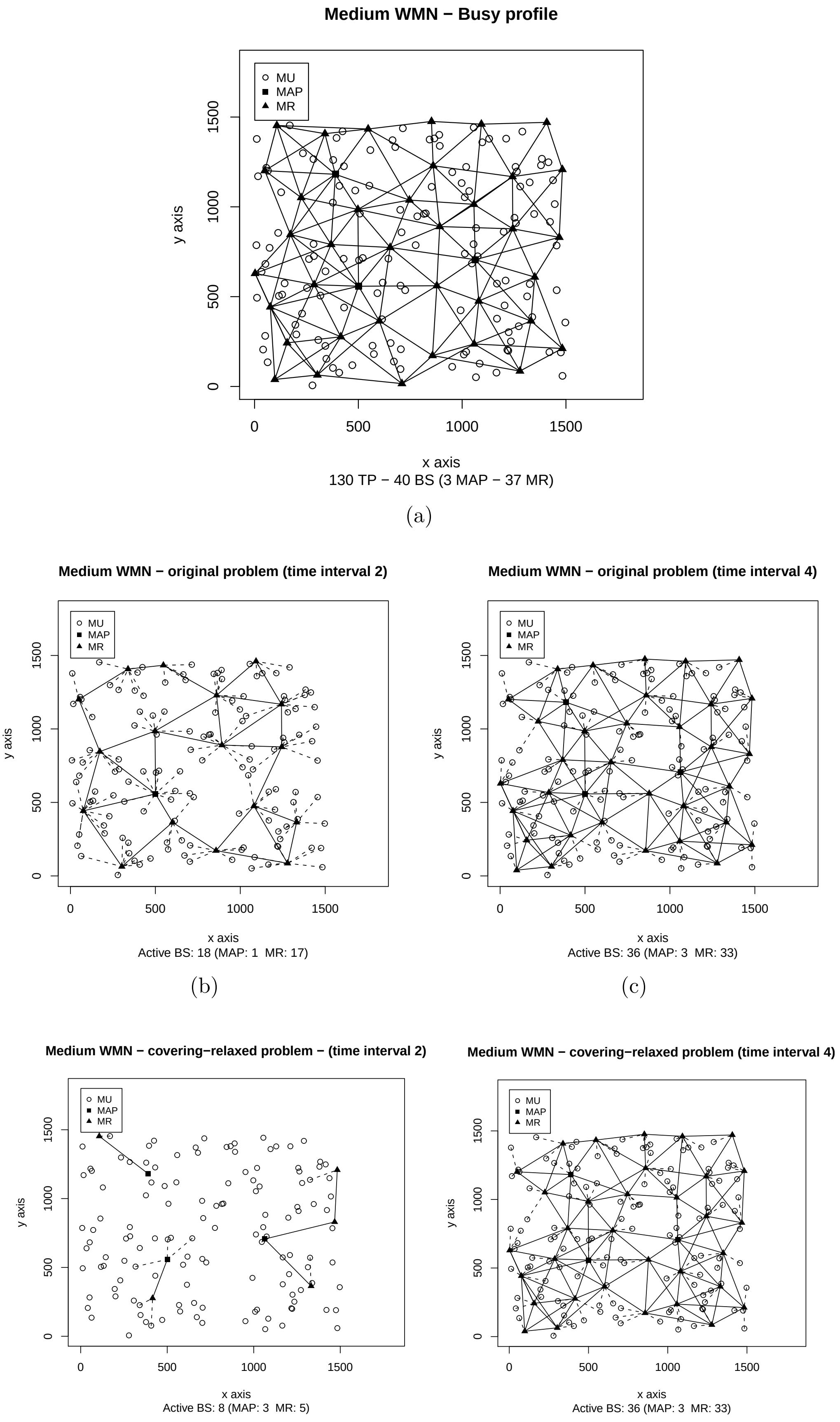


(a)

(b) (c)

(d) (e)

Figure 7.1: An example of a small **WMN** represented first with all active devices(a), then in four different cases



Medium WMN − Busy profile

(a)

Medium WMN − original problem (time interval 2)

(b)

Medium WMN − original problem (time interval 4)

(c)

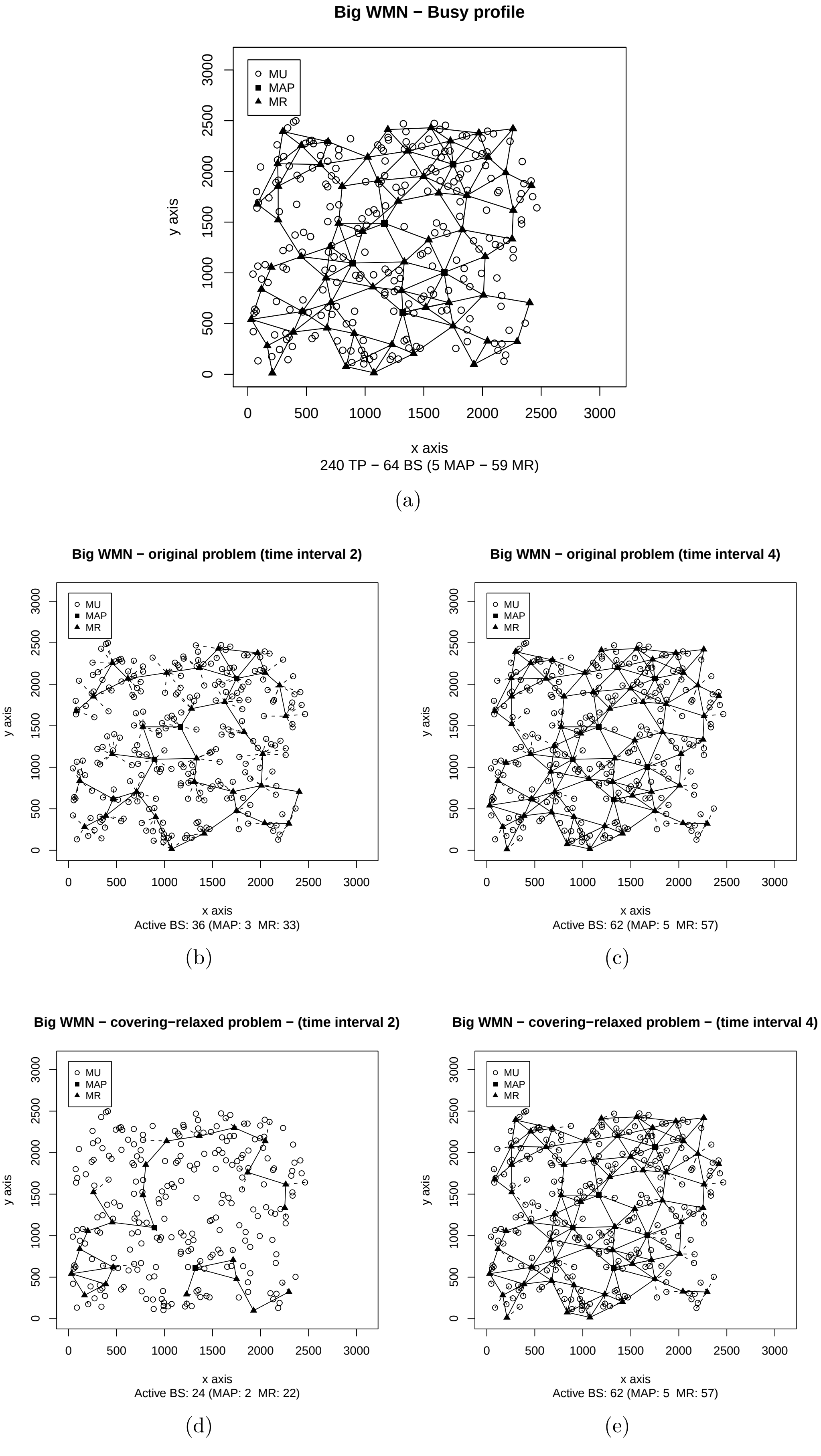
Medium WMN − covering−relaxed problem − (time interval 2)

(d)

Medium WMN − covering−relaxed problem (time interval 4)

(e)

Figure 7.2: An example of a medium **WMN** represented first with all active devices(a), then in four different cases

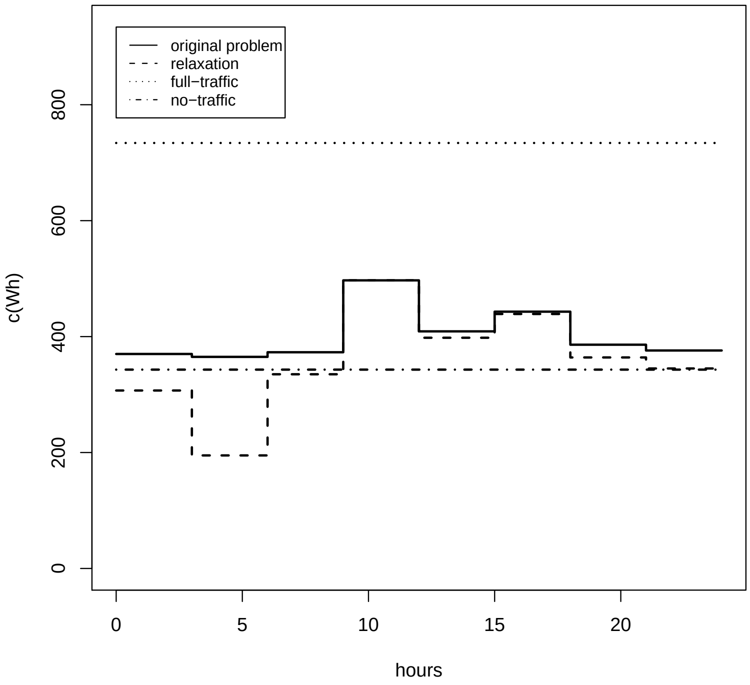


(a)

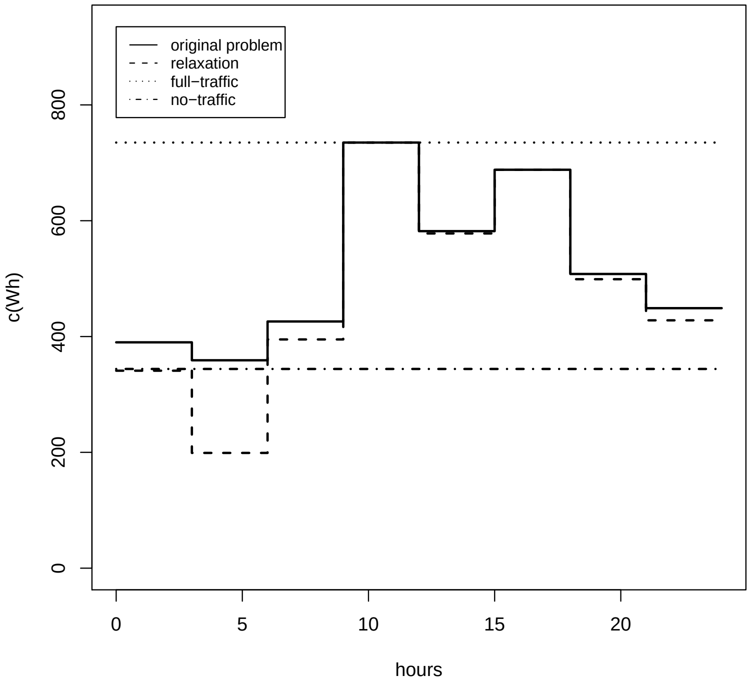
(b) (c)

(d) (e)

Figure 7.3: An example of a large **WMN** represented first with all active devices (a), then in four different cases

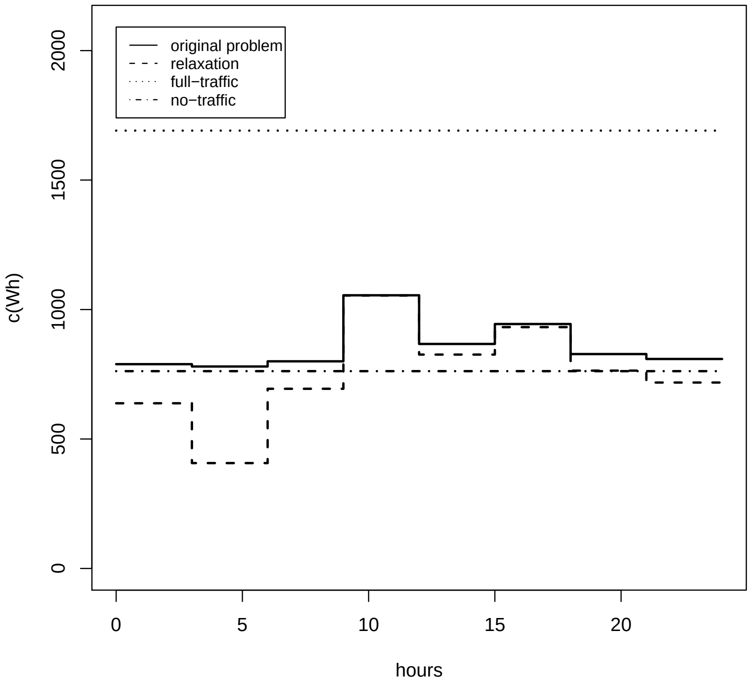


(a)

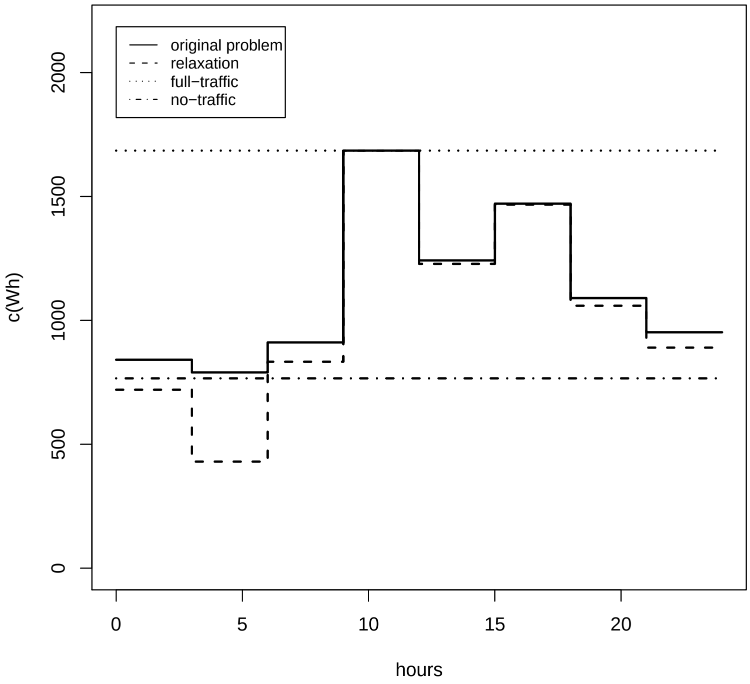


(b)

Figure 7.4: Average values of energy consumption for 150 small WMNs with both traffic profiles: (a) standard and (b) busy

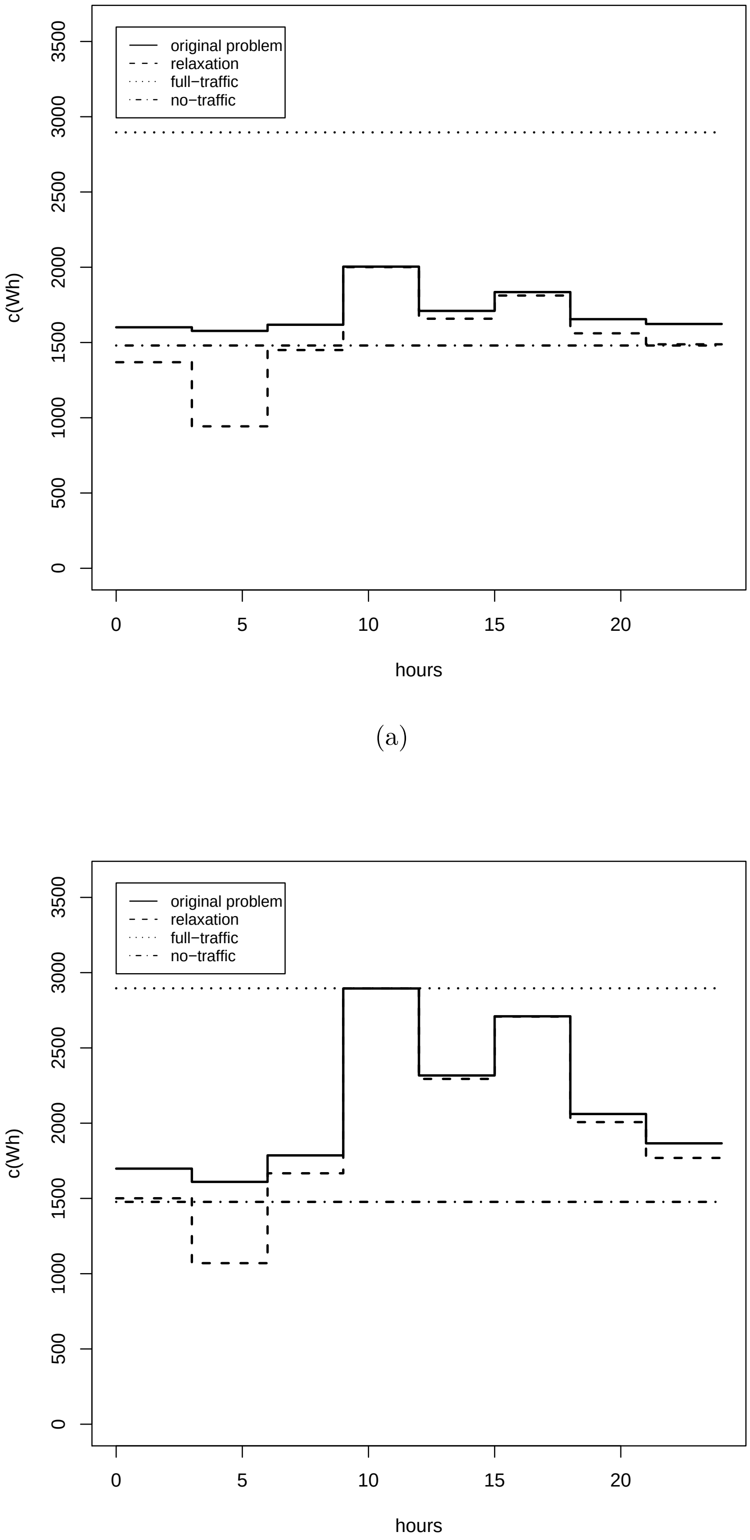


(a)



(b)

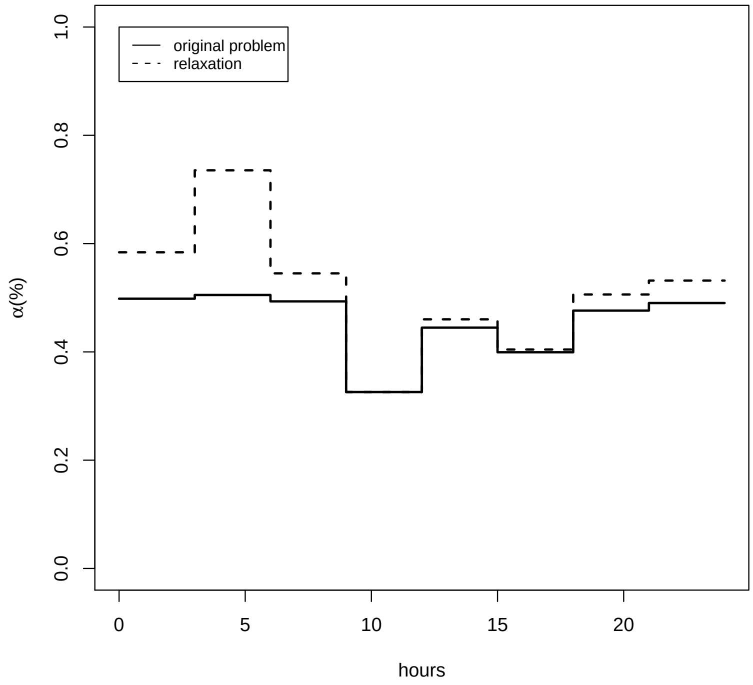
Figure 7.5: Average values of energy consumption for 150 medium WMNs with both traffic profiles: (a) standard and (b) busy



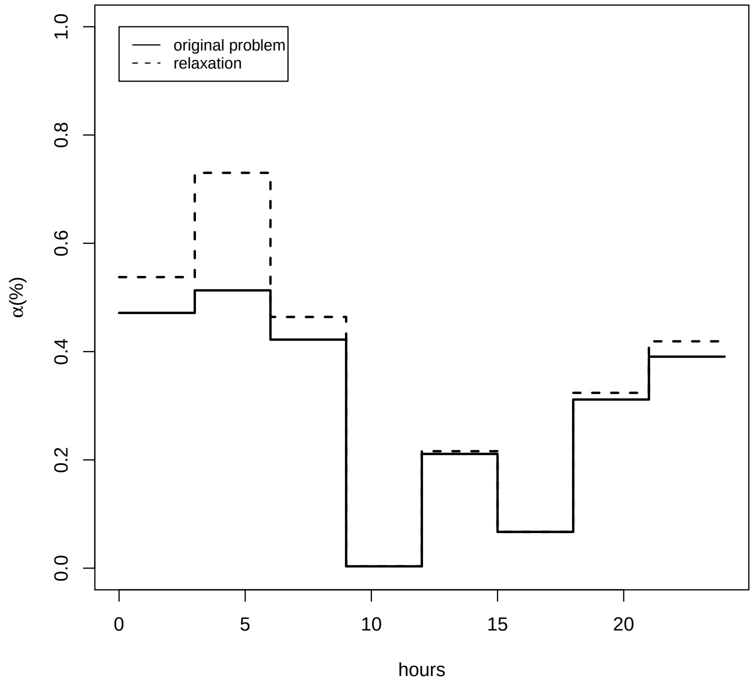
(a)

(b)

Figure 7.6: Average values of energy consumption for 150 large WMNs with both traffic profiles: (a) standard and (b) busy

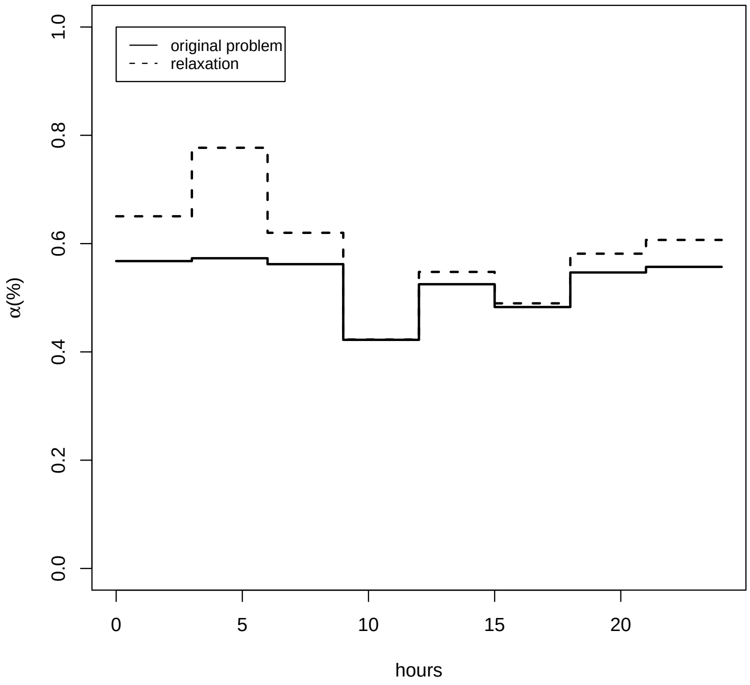


(a)

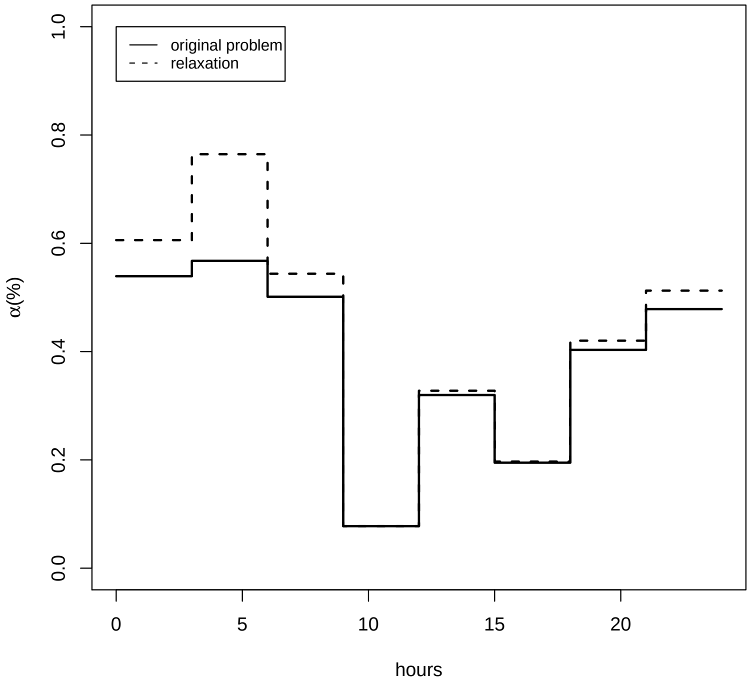


(b)

Figure 7.7: The percentage of energy saved in 150 small WMNs with both traffic profiles: (a) standard and (b) busy

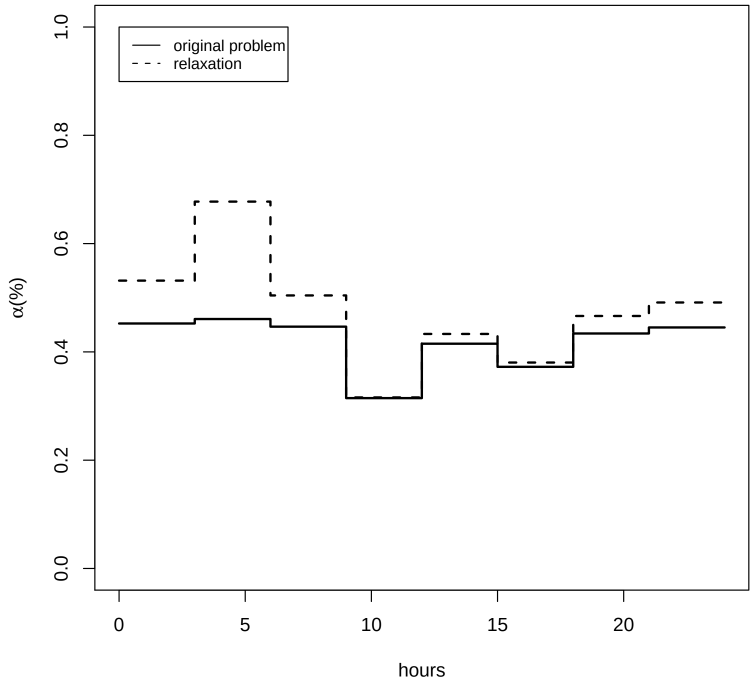


(a)

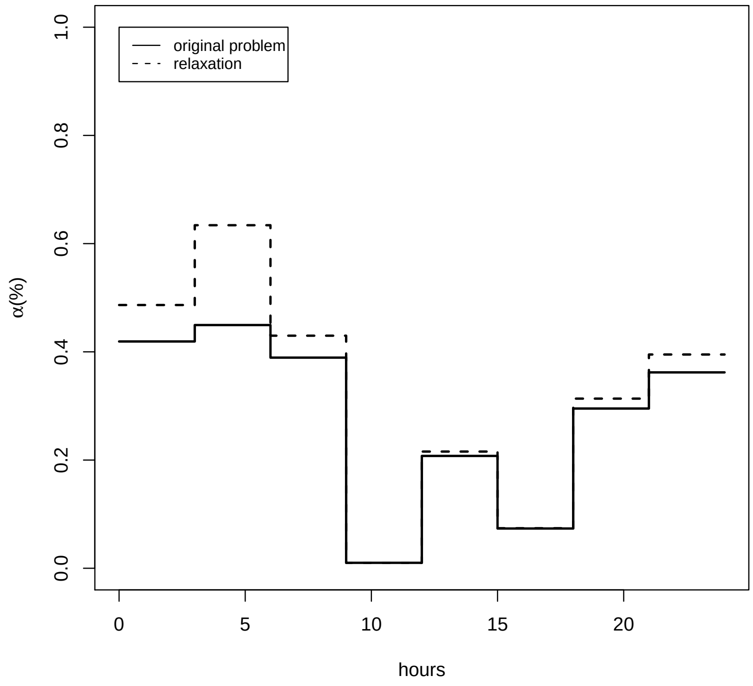


(b)

Figure 7.8: The percentage of energy saved in 150 medium WMNs with both traffic profiles: (a) standard and (b) busy

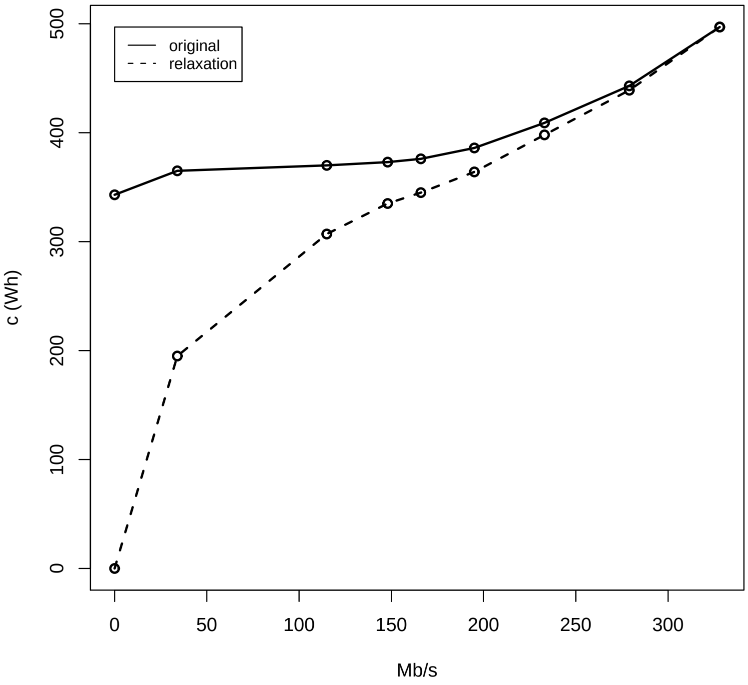


(a)

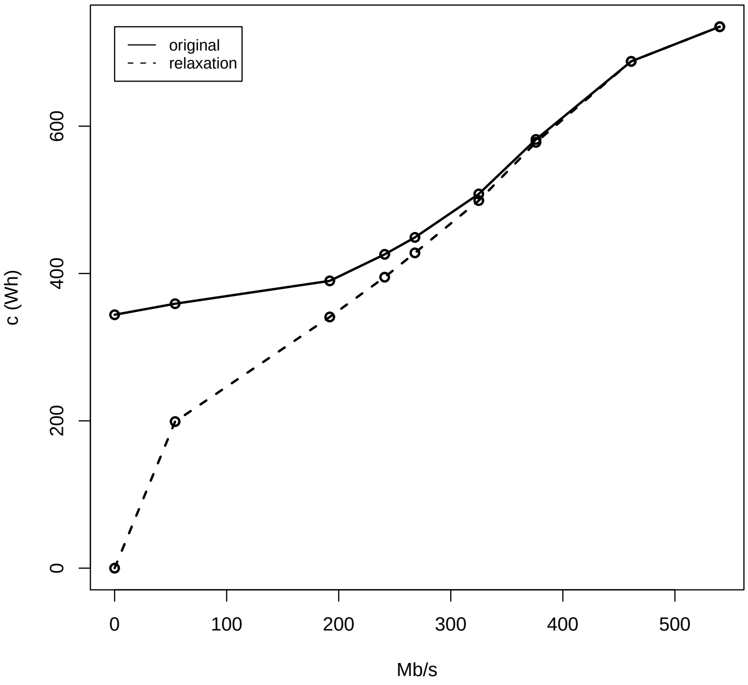


(b)

Figure 7.9: The percentage of energy saved in 150 large WMNs with both traffic profiles: (a) standard and (b) busy

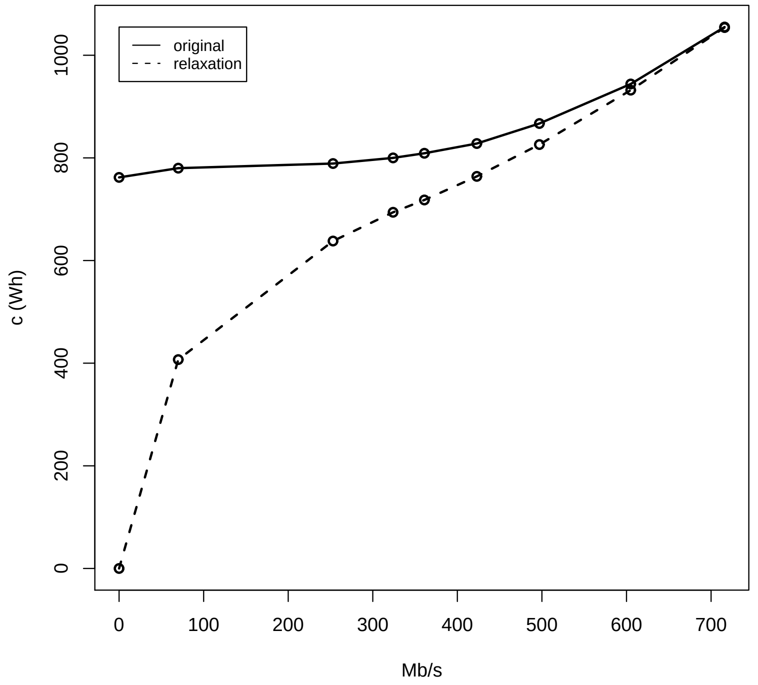


(a)

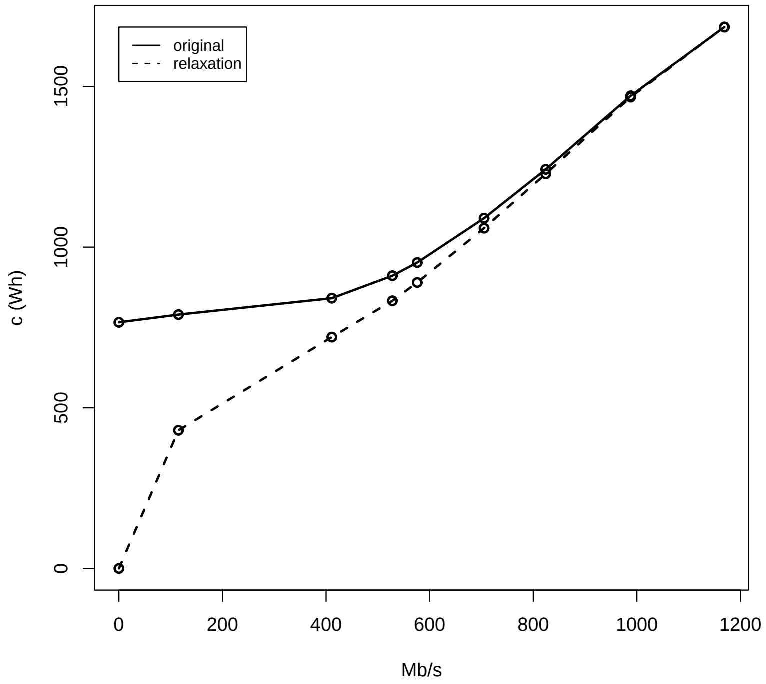


(b)

Figure 7.10: The curve of consumption according to traffic for 150 small WMNs with both traffic profiles: (a) standard and (b) busy

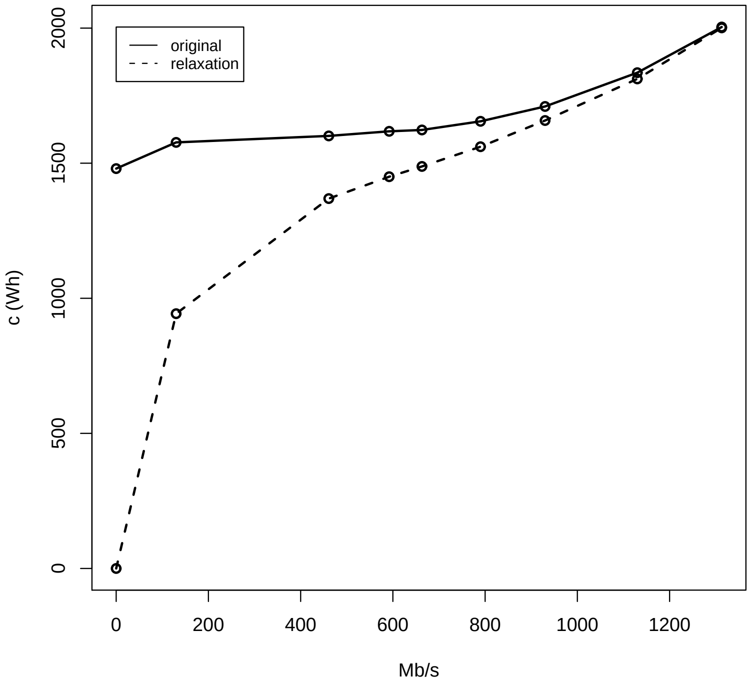


(a)

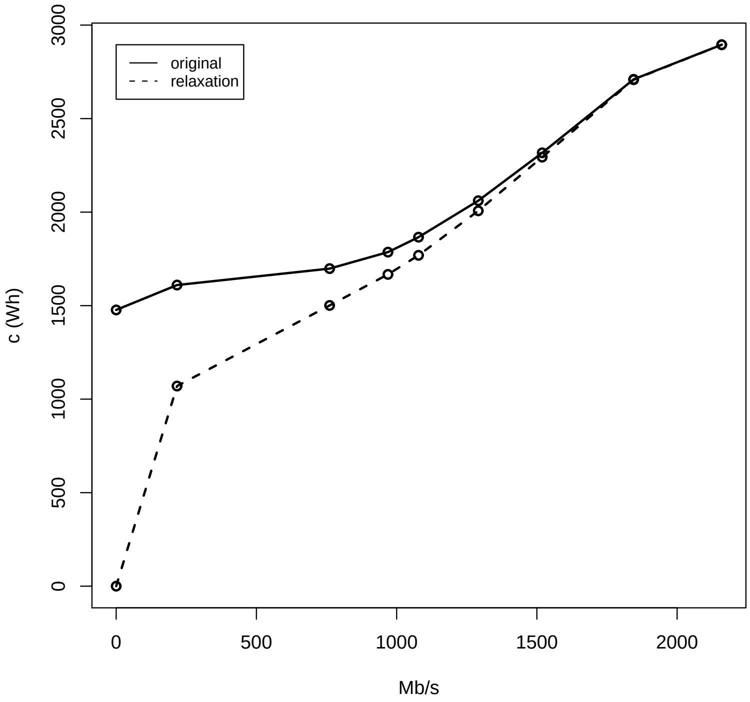


(b)

Figure 7.11: The curve of consumption according to traffic for 150 medium WMNs with both traffic profiles: (a) standard and (b) busy



(a)



(b)

Figure 7.12: The curve of consumption according to traffic for 150 large WMNs with both traffic profiles: (a) standard and (b) busy

Chapter 8

Conclusions

In this thesis we presented a model for energy savings 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. The modelling framework was not designed for instantaneous traffic variations or for considering RF management features such as AMC or cognition, but rather to provide some insights on the potential energy achievements provided by the combination of mesh networks flexibility and BS's energy management operation.

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 reassigning 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.

Appendix A

Paper accepted by *Springer MONET journal*

Our research work produced, as well as this thesis, a paper named *Energy savings in wireless mesh networks in a time-variable context* written by the author of this thesis, Filippo Malandra, in cooperation with professor Antonio Capone, Politecnico di Milano, and professor Brunilde Sansó, Ecole Polytechnique de Montreal.

The aforementioned paper has been submitted to *Springer Mobile Networks and applications (MONET) journal* and finally accepted thanks to the very positive feedbacks by the reviewers, chosen by *Springer* for the evaluation. It is expected to be published in the following months.

Here follows the latest submitted version of the article.

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

Energy savings in Wireless Mesh Networks in a time-variable context

Antonio Capone · Filippo Malandra · Brunilde Sansò

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 **WMN**s. 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 articles [9,11,2,12,13,14,1] (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 **WMN**s 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 7 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 [15]. 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 [16,17,18,19,20,21,3,22].

Good overviews of the research on green networking and methodological classifications are given in [23,24] 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 [25], 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 [15] 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 [10] that presented strategies based on the resource on-demand (RoD) concept. [9] proposed an analytical model to assess the effectiveness of RoD strategies and [11] 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. [13], 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 [12] where it is shown that the on-off strategy for UMTS **BS** is feasible in urban areas. [14] 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 **WMN**s 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 **WMN**s 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 **WMN**s.

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

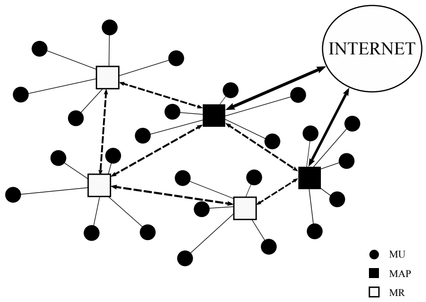


Figure 1: Architecture of the network analyzed

Mesh 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 [26]. 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 modelling approach proposed is general and can be used with any wireless technology, we have focused our analysis on WiFi **WMN**s. 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 **BS**s, 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 6.

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 [27] and [28] the characteristics of the traffic in Wireless Access Networks have been analyzed and it is shown how the traffic during the day can be divided 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 *follow* 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 [28] and [27]. 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 **BS**s 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 **WMN**s and that allow the centralized and remote control of all devices and the change of their configuration with relatively slow dynamics (hours) [29].

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 **BS**s 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 [30] 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:

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

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

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

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

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

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

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

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

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

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

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

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:

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

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

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

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:

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

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

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

$$\sum_{j \in S} \sum_{t \in T} z_{jt} \xi_j \varDelta T \qquad (12)$$

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.

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

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

Flow conservation constraints

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

(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 **BS**s that can be of different type (**MAP**s 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.

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

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

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

Best assignment constraints

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

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.

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

Summarizing model $P1$ can be presented as follows:

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

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 by 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 *n*o-traffic problem $P1_0$ and the second one, the *full-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;
- 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.

WMN size	**dimension** (m)	**tps**	**BS** (**MAP**s)
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

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.

6 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 **MAP**s), the **MAP**s 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).

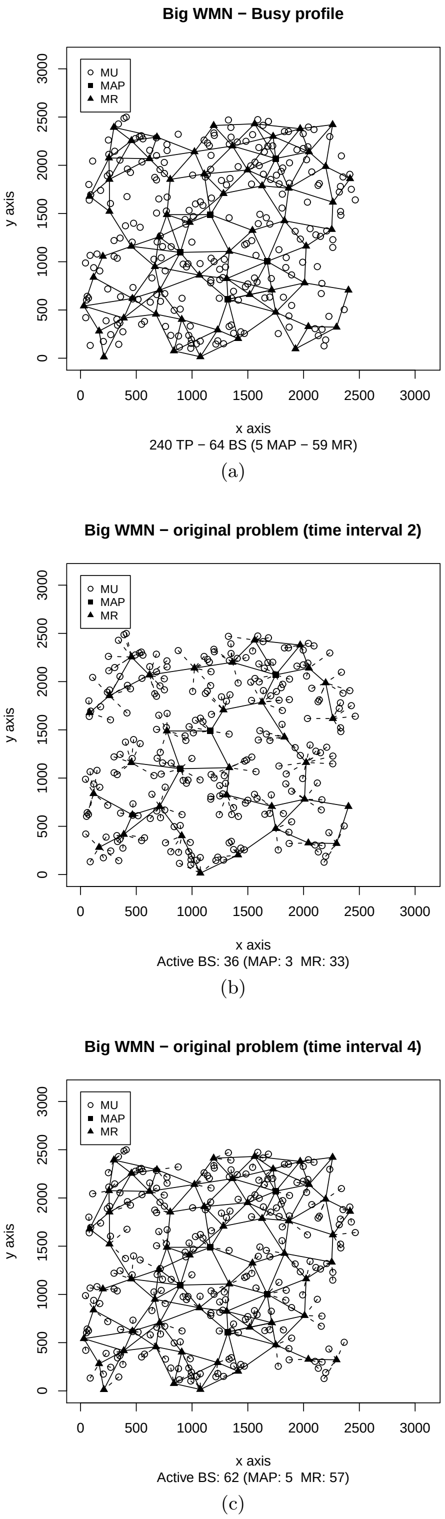
Also note that the underline will refer to the values associated to the covering-relaxed model.

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.

6.1 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



(a)

(b)

(c)

Figure 2: 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 displayed, in Figure 2, a large instance **WMN** for three different cases. The first (figure 2-a) corresponds to the wireless *distribution system* with all **BS**s active (without having used the optimization process). The second and third cases (see figures 2-b and 2-c) represent the active **BS**s after applying the optimization model for time intervals 2 and 4, that correspond, respectively, to low demand and peak hours. These figures give a visual impact of how many **BS**s we can switch off in the low traffic period while guaranteeing the covering of all the TPs and keeping the connectivity for the whole network. It can be seen that 36 (out of 64) **BS**s are active in the second time interval whereas 62 are active for the fourth. It can also be appreciated that 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 **MAP**s 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 **MAP**s) 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**s 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.

Moreover we can see that the minimum percentage of active **BS** reaches very interesting values. For the small instances we have 43.75% of the maximum (7 stations over 16). For the medium instances we have 35% (14 stations over 40) for normal traffic and 37.5% (15 over 40) for busy traffic. For the large instances we get 50% (32 over 64) for both traffic profiles. We can also note that the maximum values of active **BS**s are in almost all time intervals considerably lower in comparison with the case without optimization. For example, among all the medium **WMN**s, all the instances have in the first three intervals a maximum of 19 **BS** active over a total number of 40.

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 **MAP**s is obtained, except for interval ($t = 3$) for the large network, heavy traffic and covering relaxed problem in which a lower number of **MAP**s were installed in the worst case.

6.1.1 Energy profiles

In Figures 3 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 4 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 4 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 4 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.

	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 **BS**s 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 **BS**s for the medium **WMNs**

	Large 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	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											
			$P1$						$\underline{P1}$					
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 **BS**s for the large **WMNs**

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 5 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 $P1$ 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.

7 Conclusion

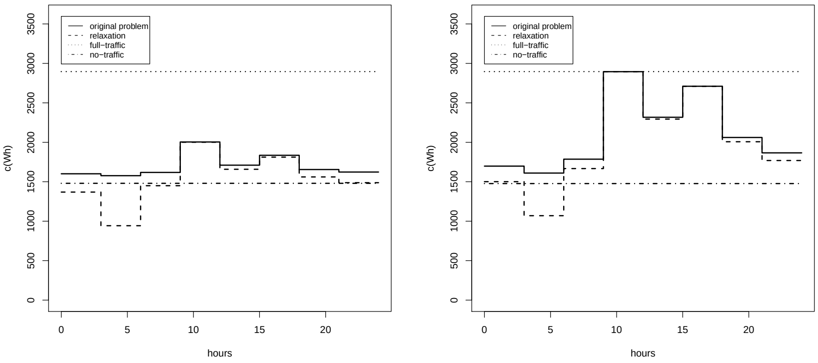
In this paper we presented a model for energy savings that takes advantage of the flexibility of **WMN** and of a careful management of **BS** operation. We created an instance generator and prepared a substantial set of instances to evaluate the model and compare them with other modelling variations. The modelling framework was not designed for instantaneous traffic variations or for considering RF management features such as AMC or cognition, but rather to provide some insights on the potential energy achievements provided by the combination of mesh networks flexibility and **BS's** energy management operation.

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.

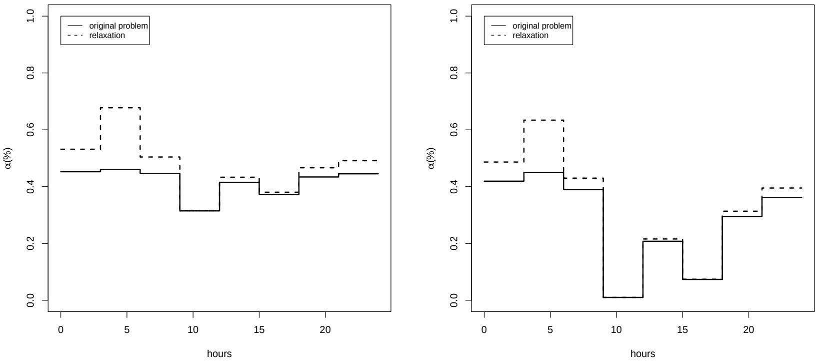
References

1. J. Lorincz, A. Capone, and D. Begusic. Optimized network management for energy savings of wireless access networks. *Computer Networks*, 55(3):514–540, 2010.
2. L. Chiaraviglio, M. Mellia, and F. Neri. Energy-aware networks: Reducing power consumption by switching off network elements. In *FEDERICA-Phosphorus tutorial and workshop (TNC2008)*, 2008.
3. L. Chiaraviglio, M. Melia, and F. Neri. Energy-aware backbone networks: a case study. In *First International Workshop on Green Communications, Dresden, Germany*, June 2009.



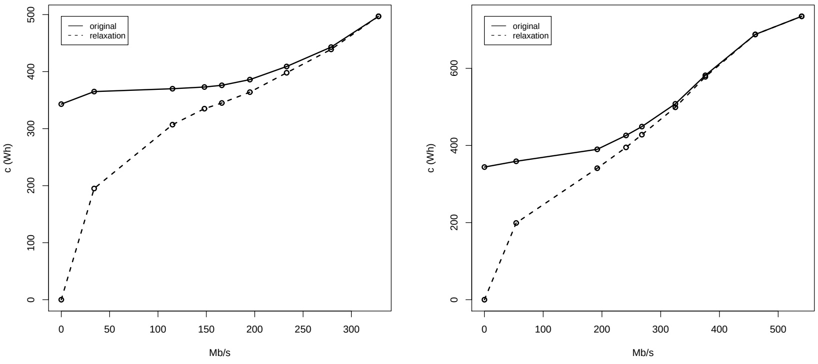
(a) (b)

Figure 3: Average values of energy consumption for 150 large **WMN**s with both traffic profiles: (a) standard and (b) busy



(a) (b)

Figure 4: The percentage of energy saved in 150 large **WMN**s with both traffic profiles: (a) standard and (b) busy



(a) (b)

Figure 5: The curve of consumption according to traffic for 150 small **WMN**s with both traffic profiles: (a) standard and (b) busy

4. The Climate Group. SMART 2020: Enabling the low carbon economy in the information age. In *2010 State of Green Business*, June 2008.
5. C. Lange and A. Gladisch. On the energy consumption of FTTH access networks. In *Optical Fiber Communication - incudes post deadline papers, 2009. OFC 2009. Conference on*, pages 1–3, mar. 2009.
6. P. Chowdhury, M. Tornatore, S. Sarkar, and B. Mukherjee. Building a green wireless-optical broadband access network (WOBAN). *Journal of Lightwave Technology*, 28(16):2219–2229, August 2010.
7. F. Richter, A.J. Fehske, and G.P. Fettweis. Energy efficiency aspects of base station deployment strategies for cellular networks. In *VTC '09*, 2009.
8. I.F. Akyildiz, X. Wang, and W. Wang. Wireless mesh networks: a survey. *Computer Networks*, 47(4):445–487, March 2005.
9. M. A. Marsan, L. Chiariviglio, D. Ciullo, and M. Meo. A simple analytical model for the energy-efficient activation of access points in dense WLANs. In *e-Energy 2010 - First International Conference on Energy-Efficient Computing and Networking*, April 2010.
10. A. P. Jardoshand K. Papagiannaki, E. M. Belding, K. C. Almeroth, G. Iannaccone, and B. Vinnakota. Green WLANs: on-demand WLAN infrastructures. *Mobile Networks and Applications*, 14(6):798–814, December 2009.
11. T. D. Todd, A. A. Sayegh, M. N. Smadi, and D. Zhao. The need for access point power saving in solar powered wlan mesh networks. *IEEE Network Magazine*, 22(3), May/June 2008.
12. L. Chiaraviglio, D. Ciullo, M.Meo, and M.A. Marsan. Energy-aware UMTS access networks. In *WPMC'08*, 2008.
13. M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo. Optimal energy savings in cellular access networks. In *Proc. of GreenComm'09*, June 2009.
14. J. Gong, S. Zhou, Z. Yang, D. Cao, C. Zhang, Z. Niu, and P. Yang. Green mobile access network with dynamic base station energy saving. In *IEICE Tech. Rep., IA 2009*, volume 109, pages 25–29, October 2009.
15. M. Gupta and S. Singh. Greening of the internet. In *Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications*, pages 19–26, 2003.
16. C. Gunaratne and K. Christensen. A new predictive power management method for network devices. *IEE Electronics Letters*, 41(13):775–777, June 2005.
17. K. Christensen, P. Gunaratne, B. Nordman, and A. George. The next frontier for communications networks: Power management. *Computer Communications*, 27(18):1758 – 1770, December 2004.
18. R. Bolla, R. Bruschi, F. Davoli, and A. Ranieri. Performance constrained power consumption optimization in distributed network equipement. In *1st Workshop on Green Communications, GreenCom1*, June 2009.
19. J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright. Power awareness in network design and routing. In *Proceedings of INFOCOM 08*, pages 457–465, Phoenix, Arizona, 2008.
20. S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall. Reducing network energy consumption via sleeping and rate-adaptation. In *Proc. of NSDI'08*, August 2009.
21. A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini. An energy saving routing algorithm for a green OSPF protocol. In *IEEE INFOCOM 2010, Work in Progress session, San Diego (USA)*, 2010.
22. L. Chiaraviglio, M. Mellia, and F. Neri. Reducing power consumption in backbone networks. In *Proc. of ICC2009*, June 2009.
23. H. Mellah and B. Sansò. Review of facts, data and proposals for a greener Internet. In *Proceedings of Broadnets09*, September 2009.
24. M. Minami and H. Morikawa. Some open challenges for improving the energy efficiency of the Internet. In *CFI08: Proceedings of the International Conference on Future Internet Technologies*, June 2008.
25. H. Karl. An overview of energy-efficiency techniques for mobile communication systems. Technical report, Report of the Working Group 7 Low-power broadband wireless communication of the Arbeitsgruppe Mobikom, DLR/BMBF, October 2003.
26. L. Badia, M. Conti, S.K. Das, L. Lenzin, and H. Skalli. Routing, interface assignment and related cross-layer issues in multiradio wireless mesh networks. *Guide to wireless mesh networks - book chapter 6*, January 2009.
27. J. Lorincz, A. Capone, and M. Bogarelli. Energy savings in wireless access networks through optimized network management. In *Wireless Pervasive Computing (ISWPC), 2010 5th IEEE International Symposium on*, pages 449–454, May 2010.
28. R. Pries, F. Wamser, D. Staehle, K. Heck, and P. Tran-Gia. On traffic characteristics of a broadband wireless internet access. In *NGI'09: Proceedings of the 5th Euro-NGI conference on Next Generation Internet networks*, pages 184–190, Piscataway, NJ, USA, 2009. IEEE Press.
29. M. Subramanian. *Network Management - Principles and Practice*. Addison-Wesley, 2000.
30. E. Amaldi, A. Capone, M. Cesana, I. Filippini, and F. Malucelli. Optimization models and methods for planning wireless mesh networks. *Computer Networks*, 52(11):2159–2171, 2008.

Bibliography

[1] J. Lorincz, A. Capone, and D. Begusic. Optimized network management for energy savings of wireless access networks. *Computer Networks*, 2010, doi:10.1016/j.comnet.2010.09.013.

[2] L. Chiaraviglio, M. Mellia, and F. Neri. Energy-aware networks: Reducing power consumption by switching off network elements. In *FEDERICA-Phosphorus tutorial and workshop (TNC2008)*, 2008.

[3] L. Chiaraviglio, M. Mellia, and F. Neri. Energy-aware backbone networks: a case study. In *Proc. of GreenComm'09*, June 2009.

[4] The Climate Group. SMART 2020: Enabling the low carbon economy in the information age. In *2010 State of Green Business*, June 2008.

[5] C. Lange and A. Gladisch. On the energy consumption of ftth access networks. pages 1 –3, mar. 2009.

[6] Pulak Chowdhury, Massimo Tornatore, Suman Sarkar, and Biswanath Mukherjee. Building a green wireless-optical broadband access network (woban). *Journal of Lightwave Technology*, 28(16):2219–2229, August 2010.

[7] F. Richter, A.J. Fehske, and G.P. Fettweis. Energy efficiency aspects of base station deployment strategies for cellular networks. In *VTC '09*, 2009.

[8] Ian F. Akyildiz, Xudong Wang, and Weilin Wang. Wireless mesh networks: a survey. *Computer Networks*, 47(4):445–487, March 2005.

[9] M. A. Marsan, L. Chiariviglio, D. Ciullo, and M. Meo. A simple analytical model for the energy-efficient activation of access points in dense WLANs. In

e-Energy 2010 - First International Conference on Energy-Efficient Computing and Networking, April 2010.

[10] A. P. Jardoshand K. Papagiannaki, E. M. Belding, K. C. Almeroth, G. Iannaccone, and B. Vinnakota. Green WLANs: on-demand WLAN infrastructures. *Mobile Networks and Applications*, 14(6):798–814, December 2009.

[11] T. D. Todd, A. A. Sayegh, M. N. Smadi, and D. Zhao. The need for access point power saving in solar powered wlan mesh networks. *IEEE Network Magazine*, 22(3), May/June 2008.

[12] L. Chiaraviglio, D. Ciullo, M.Meo, and M.A. Marsan. Energy-aware umts access networks. In *WPMC'08*, 2008.

[13] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo. Optimal energy savings in cellular access networks. In *Proc. of GreenComm'09*, June 2009.

[14] J. Gong, S. Zhou, Z. Yang, D. Cao, C. Zhang, Z. Niu, and P. Yang. Green mobile access network with dynamic base station energy saving. In *IEICE Tech. Rep., IA 2009*, volume 109, pages 25–29, October 2009.

[15] M. Gupta and S. Singh. Greening of the internet. In *Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications*, pages 19–26, 2003.

[16] C. Gunaratne and K. Christensen. A new predictive power management method for network devices. *IEE Electronics Letters*, 41(13):775–777, June 2005.

[17] K. Christensen, P. Gunaratne, and A. Nordman, B.and George. The next frontier for communications networks: Power management. *Computer Communications*, 27(18):1758 – 1770, December 2004.

[18] R. Bolla, R. Bruschi, F. Davoli, and A. Ranieri. Performance constrained power consumption optimization in distributed network equipement. In *1st Workshop on Green Communications, GreenCom1*, June 2009.

[19] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright. Power awareness in network design and routing. In *Proceedings of INFOCOM 08*, pages 457–465, Phoenix, Arizona, 2008.

[20] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall. Reducing network energy consumption via sleeping and rate-adaptation. In *Proc. of NSDI'08*, August 2009.

[21] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini. An energy saving routing algorithm for a green ospf protocol. In *IEEE INFOCOM 2010, Work in Progress session, San Diego (USA)*, 2010.

[22] F. Neri L. Chiaraviglio, M. Melia. Energy-aware backbone networks: a case study. In *First International Workshop on Green Communications, Dresden, Germany*, June 2009.

[23] L. Chiaraviglio, M. Mellia, and F. Neri. Reducing power consumption in backbone networks. In *Proc. of ICC2009*, June 2009.

[24] H. Mellah and B. Sansò. Review of facts, data and proposals for a greener Internet. In *Proceedings of Broadnets09*, September 2009.

[25] M. Minami and H. Morikawa. Some open challenges for improving the energy efficiency of the internet. In *CFI08: Proceedings of the International Conference on Future Internet Technologies*, June 2008.

[26] H.Karl. An overview of energy-efficiency techniques for mobile communication systems. Technical report, Report of the Working Group 7 Low-power broadband wireless communication of the Arbeitsgruppe Mobikom, DLR/BMBF, October 2003.

[27] L. Badia, M. Conti, S.K. Das, L. Lenzin, and H. Skalli. Routing, interface assignment and related cross-layer issues in multiradio wireless mesh networks. *Guide to wireless mesh networks - book chapter 6*, January 2009.

[28] J. Lorincz, A. Capone, and M. Bogarelli. Energy savings in wireless access networks through optimized network management. In *Wireless Pervasive Computing (ISWPC), 2010 5th IEEE International Symposium on*, pages 449–454, May 2010.

[29] Rastin Pries, Florian Wamser, Dirk Staehle, Klaus Heck, and Phuoc Tran-Gia. On traffic characteristics of a broadband wireless internet access. In *NGI'09: Proceedings of the 5th Euro-NGI conference on Next Generation Internet networks*, pages 184–190, Piscataway, NJ, USA, 2009. IEEE Press.

[30] M. Subramanian. *Network Management - Principles and Practice.* Addison-Wesley, 2000.

[31] E. Amaldi, A. Capone, M. Cesana, I. Filippini, and F. Malucelli. Optimization models and methods for planning wireless mesh networks. *Computer Networks*, 52(11):2159–2171, 2008.

[32] *Routers, etc. Evaluation Standard Subcommittee.* Small Routers, L2 Switches. `www.eccj.or.jp/top_runner/pdf/tr_small_routers-apr_2008.pdf`. 2008, oct.

[33] *Intel's website.* `www.intel.com`.

[34] B. Nordman and K. Christensen. Reducing the Energy Consumption of Networked Devices. *tutorial, IEEE 802 LAN/MAN Standards Committee Plenary Session.* `www.ieee802.org/802_tutorials/05-July/Tutorial`. 2005, jul.

[35] Lange, C. and Gladisch, A. Optical Fiber Communication - incudes post deadline papers. OFC 2009. Conference*On the energy consumption of FTTH access networks.* 1–3 . 2009, mar.

[36] P. Chowdhury and M. Tornatore and S. Sarkar and B. Mukherjee. Building a Green Wireless-Optical Broadband Access Network (WOBAN). 10.1109/JLT.2010.2044369. 0733-8724 . *Journal of Lightwave Technology.* 16,2219–2229. `http://dx.doi.org/10.1109/JLT.2010.2044369`. 2010, August.

[37] A. P. Jardosh, K. Papagiannaki, E. M. Belding,K. C. Almeroth, G. Iannaccone and B. Vinnakota. Green WLANs: on-demand WLAN infrastructures. *Mobile Networks and Applications.* 14(6),798–814. 2009, Dec.

[38] G. Vallee and T. Naughton and C. Engelmann and O. Hong and S... L. Scott. System-Level Virtualization for High Performance Computing. 636–643. 2008.

[39] E. Amaldi, S. Bosio, F. Malucelli and Yuan Di. On a new class of set covering problems arising in WLAN design. *Proceedings of the International Network Optimization Conference INOC.* 2005.

[40] E. Amaldi, A. Capone, M. Cesana,L. Fratta and F. Malucelli. Algorithms for WLAN Coverage Planning. *Wireless Systems and Mobility in Next Generation Internet.* Springer Berlin / Heidelberg. 3427, 52-65. 2005

[41] J. Baliga, K. Hinton and R. S. Tucker. Energy Consumption of the Internet. *COIN/ACOFT.* 1–3. 2007.

[42] J. Baliga, R. Ayre, W. V. Sorin, K. Hinton and R. S. Tucker. Energy Consumption in Access Networks. *OFC/NFOEC.* 1–3. 2008, feb.

[43] V. Chaudhary, C. Minsuk, J. P. Walters, S. Guercio and S. Gallo. A Comparison of Virtualization Technologies for HPC. 861–868. 2008.

[44] T. Takiguchi, S. Saruwatari, T. Morito, S. Ishida, M. Minami and H. Morikawa. A Novel Wireless Wake-up Mechanism for Energy-efficient Ubiquitous Networks. *Proc. of GreenComm.* 2009, jun.

[45] B. Sansò and H. Mellah. On Reliability, Performance and Internet Power Consumption. *Proceedings of DRCN09.* 2009, Oct.

[46] R. S. Tucker, R. Parthiban, j. Baliga, K. Hinton, R. W. A. Ayre and W. V. Sorin. Evolution of WDM Optical IP Networks: A Cost and Energy Perspective. *Journal of Lightwave Technology.* 27(3), 243–252. 2009, feb.

[47] G. I. Papadimitriou, C. Papazoglou and A. S. Pomportsis. Optical Switching: Switch Fabrics, Techniques and Architectures. *Journal of Lightwave Technology.* 21(2), 384–405 2003, feb.

[48] Texas Instruments website. `/www.ti.com/research/docs/index.shtml`.

[49] A. Eisenblätter and H.F. Geerd. Wireless network design: solution-oriented modeling and mathematical optimization. *Wireless Communications, IEEE.* 13(6),8–14. 2006, Dec.