A model for energy efficient operation of dense WLAN deployments
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This report is submitted in partial fulfillment of the requirements for the Bachelor’s degree in Computer Science. All material in this report which is not our own work has been identified and no material is included for which a degree has previously been conferred.

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Approved, 05/06/2012

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Abstract

The evolution in mobile terminal technology has led to an increase in the number of users accessing to the Internet. One of the major reasons for this is the enormous decrease in the price of the devices and the large number of new mobile services that have been created. This has motivated the creation of more wireless networks to support such devices.

Energy-efficiency has become one of the hot topics in wireless networking. This problem is particularly important in large WLAN deployments, formed by a large number of access points (APs) and mobile terminals (MTs).

We study how to reduce the energy consumption of large WLAN deployments. We develop an analytical model and then we use linear programming to find optimal network deployments, considering energy-efficiency and the data rate provided. The key idea is to maximize the number of APs that can be switched off while still providing a reasonable coverage.

In our mathematical model we analyse the main factors contributing to energy consumption in WLAN deployments. In addition, our model assumes that networks are centralized and organized into clusters.

We define our optimization problem as maximizing the data rate and minimizing energy consumption, subject to a set of linear constraints. Some of these constraints represent the connectivity of the network and require discrete variables. Therefore, this makes our problem a Mixed Integer Linear Problem (MILP), which is numerically tractable. Simulation results obtained using CPLEX show that for dense WLAN deployments we obtain an average energy saving of 33% while the coverage is only sacrificed by around 27.98%.
Acknowledgements

We would like to thank our supervisors Andreas Kassler and Peter Dely for all the help they have provided. We wish to express our sincere thanks to Pedro Miguel Ruiz Martinez, dean of the Computer Science Faculty of the University of Murcia, for his support. We also would like to thank our families and friends for their patient, help and support.
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1 Introduction

The revolution in mobile terminal technology and the growth of users that connect to the Internet wirelessly are two fundamental causes of the increase in the number of wireless network technologies, in particular Wi-Fi networks. Studies [3] indicate that this trend will increase significantly. The greater part of access to Internet will be by Wi-Fi, in particular, using the 802.11n technology.

According to ABI Research [4], the wireless equipment market is expected to grow by around 20-25% in 2013. Another new report made by DellOro Group [5] states that in contrast to the same period in 2010, the revenue in the wireless market in the third quarter of 2011 increased by more than 20%. They suggest that this increase is a result of the sharp increase in the use of these solutions in the business sector, nearly by 40%.

1.1 Problem and motivation

Several companies, campuses and large corporations have installed many Wi-Fi hotspots in order to provide a reliable connection to users. In addition, WLAN hotspots are supporting sophisticated applications that require high data rates, i.e., applications based on video streaming such as youtube, live programs, sport events, video conferences, etc. Thus, to satisfy user demands in terms of data rate and connectivity, it is necessary to increase the number of APs inside existing wireless networks. That means deploying dense WLAN networks.

However, this growth in terms of the number of APs goes against reducing energy consumption. In the majority of existing WLAN deployments APs are powered on 24/7. Furthermore, several dense WLAN deployments do not scale power consumption to the
volume and location of user demands. Therefore, some dense WLAN deployments have
an unnecessary waste of power because they do not take into account the existence of
periods in which certain APs are not necessary to guarantee the connectivity of users. If
the volume and location of users are taken into consideration, it is possible to switch on
only the required APs in order to satisfy user demands.

Network designers are starting to take into account the fact that energy consumption
of dense WLAN deployments can be reduced by switching off unnecessary APs. In par-
ticular, the energy savings in networks composed of one hundred to thousands of APs can
be particularly significant. In this context, depending on the number of users and their
location, there are low traffic periods when only several APs need to be powered on to
guarantee connectivity. By switching off idle APs, energy savings can be achieved.

However, since the achievable capacity of dense WLAN deployments depends on the
number of APs powered on, there is a conflict between the total energy consumption and
the aggregated data rate. In order to achieve energy savings, it will be necessary in some
cases to sacrifice the aggregated data rate offered. Consequently, dense WLAN deploy-
ments that do not take energy consumption into account, will result in a significantly high
amount of energy that could be saved by a more intelligent mechanism that determines
when to switch on what AP.

1.2 Goals

The main goal of this thesis is to design and solve a mathematical model that determines
several indications on what is the tradeoff between energy savings and performance. The
target is to minimize the total power consumption of APs, which is the minimum possible
amount of APs powered on to support user demands, while maximizing the aggregate data
rate offered to guarantee a minimum coverage to end users.

A centralized network management model is used for the design of the mathematical model and simulations. Through centralized network management, it is assumed that the state of the network, referring to the number of users and the demanded coverage, is known at a given point in time. As a result, there is the possibility to switch off unnecessary APs based on this information and make the management system less complex.

In addition, we consider a static scenario consisting of MTs, APs and switches in which APs are connected. This thesis is focused on dense WLAN deployments composed by a large number of APs which are grouped into clusters. Only users that generate certain traffic load are considered for energy savings in the design of the model.

We use optimization to compute which APs should be powered on based on the number of users that generate a certain traffic load. The main target is to achieve energy savings and guarantee connectivity for end users of the network at all times. This optimization model is a general model for dense WLAN deployments and is easy to adapt to many existing scenarios of this kind of networks. There are different options to model the problem but in our case, given that connectivity constraints require discrete variables, we model it as a MILP optimization problem, which is numerically tractable.

A limitation of this mathematical model is the assumption of a static scenario. For the sake of simplicity, it is assumed that users are not mobile and they need a certain data rate. In scenarios with a high association rate, the algorithm which determines which APs must be powered on/off needs to be executed frequently. Furthermore, those scenarios in which there may be frequent changes in associations between terminals and APs require the solution to be computed very quickly before the next change occurs. In contrast, in
scenarios with a low association rate, the computation time is not so tight.

1.3 Organization of the thesis

The remainder of the thesis is organized as follows. Section 2 describes related work that has been studied and the necessary concepts to understand the mathematical model which we are going to develop. Section 3 describes the mathematical model that we develop by means of examples. It includes a detailed analysis to identify the required parameters and variables. Section 4 evaluates the model and describes the scenarios that we use. It also shows the experimental results that we obtain by solving our proposed optimization problem using CPLEX. Section 5 summarizes our work and discusses its advantages, limitations and contributions.
2 Background and State of the Art

2.1 Background

The number of users accessing the Internet is increasing due to advances in technology, especially in mobile terminal technology. According to Kuhn [6], a mobile terminal is a portable computer-assisted communication system with independent data processing capacity, which can communicate as an endpoint of a wireless connection with other IT-systems. A higher demand for mobile Internet access leads to an increase in the number of wireless networks that need to be deployed. In particular, there has been a proliferation of Wi-Fi APs practically all over the world.

The demand for more public and private Wi-Fi networks to cover large areas and provide a high bandwidth to users leads to the creation of large infrastructures. Example scenarios of such big WiFi networks are Campuses, city-wide deployments or big companies.

High density WLANs refers to deployments where the number of users at a particular location is high. Thus, dense infrastructure deployments support a higher volume of users and provide a better quality. However, since network architectures need more APs in order to provide high bandwidth and coverage to the huge amount of new mobile terminal devices, their energy consumption increases significantly unless energy consumption management is considered.

2.1.1 WLAN systems

In order to identify where it is possible to achieve energy savings, we study the structure of WLANs and the elements that compose them. A service set is the set of elements asso-
associated with the WLAN. The basic service set (BSS) is the basic unit of 802.11 WLANs. BSS is composed by a single AP and all the associated stations (STAs).

One important element is the access point, APs provide the point of interconnection between mobile terminals and the wired network. They are responsible for the association and authentication of users, providing IP addresses to them and allowing the exchange of data between STAs in the same or different networks. Thus, the task of an AP in a BSS is to control STAs associated with it. The coverage area of an AP is called the basic coverage area (BSA).

Another important element is the network switch. According to [7], a switch channels incoming data from any of multiple input ports to the specific output port that will take the data towards its intended destination. APs connected by switches form a distribution set.

In small deployments, energy consumption is not an issue because the network is composed of a small number of APs and switches. However, in large infrastructures, the increase of the number of APs to provide the necessary coverage and bandwidth is not sustainable in terms of energy consumption. Since large network deployments are composed of hundreds to thousands APs connected through several switches, the performance of such a large network involves high energy costs when all APs and switches are powered on 24 hours, 7 days a week. In particular, an example of a small deployment could be a small business office where there are few employers and only a few APs are needed to provide coverage to them. In contrast, an example of large infrastructures could be the Dartmouth college campus which has around 500 APs [8].

Therefore, in some current large WLAN deployments, composed by hundred to thou-
sand APs, where APs and switches operate 24 hours, 7 days a week, it is interesting to take into account user demands in order to achieve energy savings. The key to build a sustainable model to achieve energy savings for large WLAN deployments is that there are periods in which it is not necessary to keep all APs powered on. Depending on users location and the amount of traffic generated by them, during low traffic periods, e.g. during the night, it is only necessary to power on some of the APs in order to provide the necessary coverage and bandwidth.

Based on the analysis made in [9], an interesting option to achieve energy savings is the introduction of centralized AP management in order to adapt the system to the demand of the users, although a distributed solution for this problem can be considered too. Thus, through a centralized management it is possible to check and control the global state of the system, taking into account the demand of the users. Based on the demand of the
users, APs that are not necessary to satisfy the requirements are switched off.

Green WLANs and Green Wireless Networking have been studied as good solutions for the energy consumption problem in dense WLAN deployments. Green WLANs are capable of achieving energy savings while end-user connectivity and performance do not suffer an adverse impact. It is possible to see studies about Green WLANs and Green Wireless Networking in [8] and [10] respectively. The goal of these technologies is to achieve energy savings through an analysis of users demand, adapting the energy consumption to this demand. While [10] discusses the adoption of a centralized or a distributed management, [8] adopts a centralized approach to WLAN management.

There are many studies about energy efficient networks. We find the study made in [11] particularly relevant. It proposes an analytical model to determine the effectiveness of policies to switch on/off APs in dense WLANs deployments. This study is important for us since the context of our study is similar to the context of [11]. It studies resource-on-demand (RoD) policies as a solution to achieve energy savings. RoD policies can dynamically decide which APs must be powered on/off at a given time based on the volume and location of users demand. MTs can establish an association with different APs, thus the goal is to identify a set of APs which can be switched off without dramatically sacrificing the QoS obtained by end-users. Two RoD policies have been studied in [11]; On the one hand, one policy is based on user demand, i.e. APs take into account users that are associated with them in order to decide which will be switched on/off. On the other hand, the policy is based on traffic load demand, taking into account users that are generating traffic.

However, some aspects are not considered in previous studies. One important factor which is neglected is the energy consumed by APs. Previously analysed studies about energy savings in dense WLAN deployments consider the same AP energy consumption
regardless of its model and the state in which it is. Table 2.1 shows that the power consumption varies between APs depending on the model and state. Based on values shown in the table, it is not enough to keep them in idle state and minimize the load on an AP to achieve energy savings. In particular, Aruba and Cisco systems have the same power consumption being in idle and receiving state. Thus, the best results with regard to energy savings are obtained by powering off unnecessary APs.

Another factor that must be considered is the switch power consumption since some APs are powered through the switch ports, i.e. Power over Ethernet (PoE) technology. Thus, in network scenarios that have PoE switches, the energy savings will depend on switches too. They do not depend only on APs because the energy consumption of switches increases depending on the number of APs connected to them, increasing the PoE value. Previous studies only take into account the PoE technology in order to evaluate the potential energy consumption of dense WLANs.

Table 2.2 shows the power consumption of a Cisco Catalyst 3750-E switch with different configurations and states. If a switch has PoE technology, it is capable of achieving energy savings through switching off APs that are not in use. In particular, it is possible to observe this with a Cisco Catalyst 3750-E switch with 24 and 48 ports, working at 5% and having 50% of PoE, the energy consumption is reduced to 195 and 386 W respectively by switching off all APs connected to it through PoE. However, the switch has approximately the same power consumption as a switch without PoE technology. Therefore, the only way to achieve energy savings in a switch is by powering off the entire switch or switching off ports that are not in use.

In this context, switching off some ports instead of switching off the entire switch is a good choice because it is necessary to guarantee a minimum coverage since a switch could
control APs of large coverage areas. It is not possible to switch off the entire switch because it is required to have at least one AP on in each BSS to allow associations with STAs.

| Power Consumption [W] | | |
|-----------------------|--|--|--|
| | Idle | $R_x$ | $T_x$ |
| Aruba AP-125 | 9.4 | 9.4 | 10.6 |
| Cisco AP-1250 | 9.2 | 9.2 | 10.1 |
| Meru AP-320 | 4.7 | 6.6 | 8.0 |

Table 2.1: APs consumption from [1]

<table>
<thead>
<tr>
<th></th>
<th>Ports</th>
<th>Throughput [%]</th>
<th>Power over Ethernet [%]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24</td>
<td>5</td>
<td>0</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>5</td>
<td>50</td>
<td>304 (switch)</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>100</td>
<td>0</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>100</td>
<td>100</td>
<td>509 (switch)</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>5</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>5</td>
<td>50</td>
<td>564 (switch)</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>100</td>
<td>0</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>100</td>
<td>100</td>
<td>978 (switch)</td>
</tr>
</tbody>
</table>

Table 2.2: Switch consumption from [2]

### 2.1.2 Relation between data rate and coverage

In this section, we study some necessary concepts based on the information of [12] and [13] in order to understand and implement our mathematical model.
Firstly, it is necessary to know how to obtain the potential data rate that each MT can achieve through an association with a given AP. The obtained throughput in terms of data rate is conditioned by the number and location of users in the network, and the modulation and coding scheme (MCS) used by these users. The data rate $R$ is shared by $N$ users; each user achieves approximately a throughput of $R/N$ if fair queuing best-effort communication is assumed based on [14]. However, if the possibility that different MTs could have different MCS is considered, as it is possible to see in [15], the data rate obtained by each MT will depend on the MCS used too. Wireless technologies have a rate adaptation algorithm that adapts the MCS according to the quality of the radio channel, adapting also the bit rate and robustness of data transmission. Therefore, different MTs can have different modulation schemes at the same time and the data rate obtained will depend on their modulation scheme. For example, BPSK will obtain the lower values and 64-QAM the higher values in data rate.

Another parameter that conditions the throughput of end-users is the distance between APs and MTs. The log-distance path loss model will be applied based on this distance in order to calculate users throughput. Log-distance path loss model indicates that the received signal strength decreases logarithmically with distance, this will be used to indicate the average of received power based on [16].

\[
\mathcal{PL}(dB) = \mathcal{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad (2.1)
\]

where $n$ is the path loss exponent, which indicates the rate at which the path loss increases with distance, $d_0$ is the close-in reference distance which is determined from measurement close to the transmitter and $d$ is the transmitter-receiver separation distance.

In order to compute $\mathcal{PL}(d_0)$, Freespace Path Loss is used based on [13]:

11
\[
\overline{PL}(d_0) = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 \text{dB} \tag{2.2}
\]

where \( d \) is the distance in meters between transmitter and receiver and \( f \) is the signal frequency in hertz. The next step is to calculate the receiver power, \( R_x \), the formula is:

\[
R_x = \overline{PL} - T_x \tag{2.3}
\]

where \( R_x \) is the receiver power, \( T_x \) the transmit power and \( \overline{PL} \) the path loss value. The next step is to obtain the results in terms of signal noise to ratio [17]:

\[
SNR_{dB} = R_x - P_{\text{noise,dB}} \tag{2.4}
\]

where \( R_x \) is the previous value obtained in the equation 2.3, and the \( P_{\text{noise,dB}} \) is the average power of interferences that can appear in the scenario.

### 2.1.3 Background and mathematical optimization

Once the essential elements that constitute WLAN deployments have been analysed and we have specified how to calculate the offered data rate, we provide a description of our mathematical model.

We model our problem as a mathematical optimization model. Based on the previous study of the elements of the network and their state, we identify a set of variables which form the model of the system. These variables will be described in detail in section 3. We also define a linear function to optimize as the sum of the following two objectives: maximize the total data rate offered to end-users and minimize the total power consumption of APs. Furthermore, in order to accomplish both objectives, it is necessary to establish some constraints for this linear function. They are described in section 3.
Once the linear function of this mathematical model is defined, according to [18], a linear programming problem must be defined as a problem of maximizing or minimizing a linear function subject to linear constraints. In this regard, a conflict arises because there is one objective to be maximized and another to be minimized. In order to solve this conflict, the same criteria for both, will be adopted. Instead of calculating the minimum total energy consumption, the minimum value for total energy consumption will be maximized. Thus, the condition established by the definition of a linear function is satisfied, having a problem of maximizing a linear function subject to linear constraints. In addition, since the linear programming problem that must be defined has some constraints a starting basic feasible solution may not be readily apparent. For this reason the Big M method is used. The Big M method is a version of the Simplex Algorithm that first finds a basic feasible solution by adding ”artificial” variables to the problem [19].

There is a significant issue to consider regarding the identified variables that compose the linear constraints since integer and continuous variables are mixed. According to the definition of mixed-integer linear programming [18], MILP problems have continuous and integer variables which appear linearly, and hence separably, in the objective functions and constraints. Therefore, this problem is identified as a MILP problem.

The tool selected to solve this mathematical model is CPLEX [20]. It has been chosen because this optimization software provides flexible, high-performance mathematical solvers for MILP problems.

Once we have defined our general approach, we examine how the best solution is chosen. Thus, firstly it is necessary to create a point set that represents the different possible solutions for a given network scenario and then, the best point is determined. According to [12] the necessary concept for this is the Pareto optimality which is defined as follows:
**Definition 1** Pareto optimal: A point, \( x^* \in X \), is Pareto optimal if there does not exist another point, \( x \in X \), such that \( F(x) \leq F(x^*) \), and \( F_i(x) < F_i(x^*) \) for at least one function.

These points are Pareto optimal because it is impossible to find other points that improve at least one objective without negatively affecting the other objective.

Additionally, in order to choose the best solution contained in the Pareto optimal point set, it is necessary to establish the hypothetical optimal solution that improves both objectives. Therefore, another concept will be defined for that, the Utopia Point, defined as follows [12]:

**Definition 2** Utopia Point: A point, \( F^0 \in Z^k \), is a Utopia Point if for each \( i = 1, 2, ..., k \) \( F_i^0 = \min_{x} \{ F_i(x) \mid x \in X \} \)

![Figure 2.2: Utopia point](image)

In general \( F_0 \) is unattainable, the best solution is the point as close as possible to the Utopia Point. In Figure 2.2 an example is presented to show this concept, the Pareto Frontier is the set of choices that are Pareto optimal. Figure 2.2 shows the set of feasible
points and a possible infeasible point based on the fixed objectives [21].

For this model, the calculation of the closer point to the Utopia Point is done through the weighted min-max formulation [12], given as follows:

\[
U = \max_i \{w_i [F_i(x) - F_i^0]\}
\]

(2.5)

where \(w_i\) is the weight for each objective and \(\sum_i w_i = 1\).

In the same context as [12], an additional unknown parameter \(\lambda\) is introduced. Therefore, by varying the weights in (2.5), we can obtain the complete Pareto Optimal set. Thus, the method eliminates the possibility of unique solutions:

Minimize \(x \in X, \lambda\)

subject to

\[w_i [F_i(x) - F_i^0] - \lambda \leq 0, \ i = 1, 2, \ldots, k.\]

(2.6)

This function is applied to both objectives, trying to minimize \(\lambda\), but the two different objectives functions have different units. As a result, objective functions should be transformed, such that they are dimensionless. According to [12] the best way to transform objective functions regardless of their original range, is given as follows:

\[
F_i^{\text{trans}} = \frac{F_i(x) - F_i^0}{F_i^{\text{max}} - F_i^0}
\]

(2.7)

where \(F_i^{\text{trans}}\) takes values between 0 and 1, thus, we can refer to it as normalization, \(F_i^{\text{max}}\) is the maximum objective function values and \(F_i^0\) is the Utopia Point for each objective.
2.2 State of the Art

The previous studies we have considered about energy efficiency in wireless networks that we analyse are [11], [10], [22], and [8]. We provide a brief summary of each one and highlighting their assumptions, limitations, and benefits.

Marsan et al.[11] describe the effectiveness of resource-on-demand policies for energy-efficient operation in dense WLANs. They demonstrate that energy savings in dense WLANs can be achieved through switching off APs which are not used by any STA. Two different RoD policies are studied under different traffic loads for dynamically switch on/off WLANs APs: Association-based policy and Traffic-based policy.

This study makes several assumptions. It considers centrally managed and dense WLANs, composed by a large number of APs, grouped into clusters in order to take advantage of the overlapping coverage to achieve energy savings. Therefore, an easy model capable of adapting to different scenarios is built.

The performance obtained using a distributed or a centralized approach is analysed. The distributed approach is less effective in this context because in this case, each AP needs to distribute information about traffic load and number of active users to the rest of APs. Thus, it is necessary to create a distributed algorithm. As a result, the complexity of the distribution is increased. However, through a centralized management, thanks to centralized solutions for dense WLANs management provided by several AP vendors, it is possible to establish one centralized AP, which can manage all information about traffic load and the number of active users. By means of this technology, one central AP has the global state about the whole WLAN, and the central AP can implement an appropriate algorithm capable of taking decisions to achieve energy savings and guarantee the QoS offered to end-users.
Marsan et al. [11] made an elaborated analysis of two RoD policies, in particular association-based and traffic-based policies are considered for AP switch on/off based on a continuous time Markov Chain (CTMC) model of a cluster of APs. Association-based policy considers the number of MTs associated with APs in the cluster for switching on/off APs. In contrast, traffic-based policy considers MTs that are generating traffic.

Numerical results show that power savings around 87% during low traffic periods can be achieved by applying both policies, and this is an important fact to consider. However, results change when the association-based policy is used during peak traffic periods. During peak traffic periods, through an association-based policy no power savings are obtained, since all APs must be on at all times. This is an significant inconvenience. The traffic-based policy is able to solve partly this situation. The minimum power savings that are achieved at the peak traffic hour by using this policy is around 10%. In this respect, traffic-based policy adapts the number of active APs more appropriately to the actual traffic demand.

Consequently, despite the simplicity and effectiveness of the association-based policy, through more dynamic policies like traffic-based policy, if the policy is carefully designed, it is possible to provide better overall performance.

We find this reference very interesting in many respects. Firstly, we assume the same scenario context since energy savings are studied over dense WLANs. In addition, results are obtained using centrally managed WLANs, where APs are grouped into clusters to take advantage of overlapping coverage in order to guarantee good QoS. Based on these results, we will consider a central management and clustering for dense WLAN deployments for our mathematical model.
Moreover, this document has an intensive explanation about the resource on demand policies to achieve energy savings while the QoS is guaranteed. It has provided us with the necessary concepts to understand them and the importance of RoD policies within the field of energy savings in WLANs. We have analysed the two different approaches. Based on these analyses and considering that we want to achieve energy savings during peak periods too, we will adopt a traffic-based policy in order to achieve better overall performance.

As a limitation, since this study is not focused on the exact determination of the performance received by users, they do not consider one issue. If several MTs are associated with the same AP, the throughput they achieve is reduced. In addition, they consider that the bandwidth is fairly shared among users associated with the same AP. We will consider the possibility of MTs using different modulation schemes when an AP is shared, conditioning the throughput obtained.

Marsan et al.[10] analyses the problem of energy consumption inside the Information and Communication Technology (ICT) and discusses the relevance and the impact of research in the field of green technologies to solve this problematic. ICT is a potential technology to achieve energy savings, it can be instrumental for a 17-22% reduction of the total energy consumed in all sectors. However, the widespread use of ICT leads to a huge global energy consumption (2% to 10% of the world power), in particular about one third of this percentage is due to networking. Furthermore, the energy consumed by ICT is specially critical in some areas, thus a trade-off appears between using ICT and the energy consumption. This fact has led to an interest in two fields: ICT for energy efficiency and energy-efficient ICT. Despite the increasing number of researches in this fields, it is not a simple task to study.
There is another field about energy savings, Green Networking. It is a kind of research that also takes into account the energy consumed by the production, deployment, and end-of-life disposal of the devices. However, since research efforts are focused on reducing networking operational cost, the research is focused on energy-efficient networking, which focuses on the energy needed to operate a network.

The authors of this study try to find the different issues that condition energy-efficient networking, in particular they establish three different questions:

1. The first question discusses which kind of networks can offer best results in terms of energy savings. Two paths are proposed for this purpose: energy-efficient hardware and sleep modes for networks elements.

Since today’s equipments have an energy consumption almost independent on the traffic load, sleep modes must be considered, i.e., switch off some of the network elements based on the traffic load, providing the desired level of QoS.

The study concludes that in fixed networks the majority of the energy spent is located in the periphery. In contrast, in cellular networks the portion of the network that absorbs almost all energy is located from the core network to the base stations. Thus, in cellular networks the energy share to power base stations is largely predominant. As a result, it is considered that base stations are the best candidates for energy-efficient approaches.

Moreover, the location of energy consumption in dense corporate WLANs, composed of thousands of APs and cellular networks is similar. The same considerations about energy savings are established for the case of dense WLANs, where APs are the best candidates to achieve energy savings.
2. The second question evaluates the efficiency of energy-efficiency equipment in comparison with sleep modes in order to achieve energy savings. In this respect, the authors consider an ideal simple scenario, in which cells and the traffic of cells are the same. In addition, if any BS is put in sleep mode, another BS can provide coverage and absorb the traffic.

Although some energy-efficient equipments can offer good results, it is not a reason to drop the need for sleep modes. The authors determine that energy-efficient equipment is important when there are small fluctuations in the traffic load, while sleep modes are important in order to exploit large traffic load fluctuations. They conclude that sleep modes have less problems in achieving energy fairness, and the gain achieved with sleep modes is quite relevant.

3. The third question analyses the necessity of effective energy management algorithms, considering centralized and distributed algorithms. The target of these algorithms is to identify which BSs to switch off for a given traffic level and spatial distribution, ensuring a given QoS constraint. A brief explanation of centralized and distributed algorithms is presented. Centralized algorithms are simple although the necessary information about traffic load is distributed over BSs, but this fact does not help distributed algorithms, since the optimization of the network configuration is more complicated.

Marsan et al.[10] highlights that base stations are the best location for the adoption of energy-efficiency in cellular networks. This situation can be extrapolated to dense corporate WLANs, where access points are the best option to achieve energy savings. The necessity of sleep modes is intrinsically presented in conjunction with the development of energy-efficient network components. We find the analysis made about the
necessity of sleep modes and considering the traffic load very relevant, and these two facts are crucial in our model. In addition, although it is a brief comparison, we find the comparison between a centralized and distributed algorithm really interesting.

We consider two limitations of this model. First of all, it considers a static energy consumption of BSs. In real scenarios, the core network elements usually have a higher consumption than the peripheral elements and also the consumption depends on the traffic load too. Secondly, we find another limitation in the assumption that if a BS is powered off, another BS can offer coverage to MTs associated with the powered off BS and it absorbs the traffic, which may not always be possible.

In our case, we are considering a centralized algorithm to switch on/off APs without taking into account the distributed part. This document provides ideas to develop a complete system, while we have considered a centralized algorithm.

Richter et al.[22] provides a deep analysis in order to minimize the impact of ICT, specially in cellular networks. The authors analyse the improvement of the power consumption on two levels: Firstly, focus is drawn to the optimization of individual sites, introducing energy-proportional equipment. Secondly, network deployment is analysed, trying to improve it. This study is based on macro sites with a small number of devices (micro base stations).

Richter et al.[22] made a study of cellular site with different site densities. They study the power consumption influenced by inter site distance and the average number of micro sites per cell. Moreover, they consider a hybrid approach formed by a macro base station and some micro base stations. They compute the optimal inter site distances to optimize the area power consumption. In scenarios where micro base stations are presented, the energy savings are moderate in full load scenarios. In micro sites, the power consumption
is inversely proportional to average traffic load.

By analysing this paper we realize that it is better to have a higher number of APs with low power consumption instead of less APs consuming an immense power consumption for the same area. This is important because it is possible to switch off part of the network through switching off some APs, achieving energy savings and ensuring the demanded coverage to end-users. If the option of few APs with immense power consumption to cover large areas is selected, a problem appears since if one of them is switched off, a part of users located in its coverage area could lose the connection.

We also find a limitation in this study if a hybrid approach is used. The total power consumption is the sum of the macro and micro base stations. There are cases where it is not necessary to have the presence of macro base stations because with micro base stations the demanded service can be accomplished. Thus, if the demanded service is considered, it is possible to achieve energy savings.

There are two main differences with our study: we have not considered the utilization of macro base stations because we can ensure the necessary coverage through micro base stations. We have not calculated the optimal distance between APs. Our study is based on existing networks where different distances between APs are studied, and we make a cluster of the existing APs in the network. However, it is a fascinating option to consider the optimal APs distance for new WLAN deployments. A good assumption they considered is that the power consumption depends on the size of the coverage area and the degree of the desired coverage.

Jardosh et al.[8] studies WLAN deployments and their energy consumption. Authors study how to save the maximum energy without losing quality of service. The adoption of
resource on-demand (RoD) strategies for WLANs is proposed, powering on/off dynamically APs of the WLANs based on the volume and location of user demand. Thus, making a deep analysis about the behaviour of the network in terms of energy wastage, they propose and implement a SEAR (Survey, Evaluate, Adapt and Repeat) policy-driven RoD policy for dense WLANs. They assume a centralized management policy of APs to simplify configuration management. Through experiments made in two different scenarios, Intel Corporation in Oregon and Dartmouth college campus with 125 and 500 APs respectively, they determined the efficiency and performance of two different classes of operating strategies, demand-driven and schedule-driven. For the first one, demand-driven, the policy adopted is to switch on/off the APs based on the number of users at a given time. The second one, schedule driven, relies its policy on historical WLAN usage patterns in order to switch on/off the APs using pre-determined schedules. The SEAR policy comprises four main stages: green clustering, user demand estimation, topology management and user association management dependent between them. The first stage is responsible of forming the cluster choosing a central AP for managing. Using the clusters formed in the previous stage, SEAR initiates a cycle to estimate users demand and performance. With these statistics of channel utilization per AP and number of clients associated to each AP, the main AP in the cluster chooses which secondary APs can be powered on/off within a cluster. In order to avoid the overload of APs and consequently user re-association, SEAR policy switches clients between APs to balance the load detected within a cluster. Finally, SEAR evaluates the performance obtained in order to check if all requirements are accomplished. This model obtains a significant performance benefit (46% reduced consumption), and it is simple to apply to real scenarios.

We identify two limitations for this model. One is about schedule-based policy in terms of adaptability. If it is based on previous statistics analysis, it is not adjusted to a new possible scenario. In addition, the interval that SEAR needs to be executed is not
specified, i.e. if the interval is too short, a lot of computing resources will be consumed. In contrast, if the interval is too long problems of overload could appear because if users are not distributed uniformly, they can be associated to the same AP in the beginning of the interval time, causing an overload. The main difference with our approach is that we do not consider client switches in order to avoid overload in a secondary AP. We only consider as a constraint that a user obtains a minimum data rate. Another difference is that we only take into account users demands at a given point in time. We do not use historical WLANs usage patterns.

2.3 Summary

In the previous sections, the different terms that concern the design of our model have been analysed and discussed. The features of the two main elements of wireless networks, APs and switches, have been analysed. In particular, the analysis is focused on energy consumption of these elements in dense WLAN deployments.

The performance of Green WLANs in previous studies is analysed. Two different RoD policies for dynamically switching on/off APs in order to achieve energy savings, association based policy and traffic based policy are compared. The performance of each one to choose the most adequate for this mathematical model is evaluated. We have identified some factors not considered in previous studies that could be relevant for this model.

Furthermore, for each previous document studied, a brief summary is made, analysing its important features, advantages, limitations, and results obtained. Based on the background and state of the art, we can conclude that it is possible to achieve energy savings in dense WLAN deployments by switching off unnecessary APs depending on traffic load and the association of MTs, especially in low traffic periods.
We develop a mathematical model for achieving energy savings in dense WLAN deployments. We identify a trade off in this task because there are two main objectives to reach: reducing the total energy consumption and maximizing total data rate offered to MTs.
3 Model Design

3.1 Introduction

In a typical WLAN scenario, MTs can establish an association with different APs. An association between one MT and one AP conditions the QoS obtained. In particular, in real scenarios, stations are associated depending on various factors. The main factor is the Received Signal Strength Indicator (RSSI). In this regard, the impact of this factor will be analysed through a simple wireless scenario under different association combinations of MTs with APs.

Figure 3.1 depicts a simple scenario composed by two APs and two MTs in a possible location. We analyse our results in terms of the following metrics: total data rate, total power consumption and power over throughput under different association combinations. Power over throughput is the average energy per bit of information transmitted.

Figure 3.1: Possible scenario
Figure 3.1 shows a possible scenario in which two APs offer two different coverage areas. The coverage obtained by a certain MT will depend on the distance between this MT and the available APs. In particular, $AP_1$ and $AP_2$ offer the same achievable data rate: 54 Mbps in the closest distance of the AP (represented by the figure with red and green colours respectively), and 6 Mbps in the farthest distance (represented by the figure with blue and purple colours). Thus, depending on how MTs establish associations with APs, four different configurations are possible in this scenario:

1. In the first configuration, $MT_1$ is associated with $AP_1$ and $MT_2$ is associated with the $AP_2$. As a result, $MT_1$ and $MT_2$ obtain a data rate of 54 Mbps. In this configuration, both APs must be powered on, having energy consumption of 20W (10W per AP). The total data rate obtained is 108 Mbps and the power per bits transmitted is \( \frac{20W}{108Mbps} = 0.1851 W/Mbps \). This configuration presents the advantages of obtaining the maximum possible data rate for both MTs and obtaining the minimum value for the power per bits transmitted for this scenario. As a disadvantage, the maximum power consumption value for this scenario is reached, 20 W.

2. In the second configuration, mobile terminals $MT_1$ and $MT_2$ are associated with $AP_1$. Thus, $AP_2$ can be switched off. In this configuration, $MT_1$ and $MT_2$ obtain 27 and 3 Mbps respectively, being the total data rate 30 Mbps. According to the throughput concept definition given in 2.1 section, since the bandwidth is shared, $MT_1$ obtains \( \frac{54Mbps}{2} = 27Mbps \), $MT_2$ obtains \( \frac{6Mbps}{2} = 3Mbps \), and the power per bits transmitted is \( \frac{10W}{30Mbps} = 0.333 W/Mbps \).

3. In the third configuration, $MT_1$ and $MT_2$ are associated with $AP_2$. As a result, $AP_1$ can be switched off. In this configuration, $MT_1$, $MT_2$ obtain 3 and 27 Mbps respectively, and the total data rate is 30 Mbps. Since the bandwidth is shared in this case too, $MT_1$ obtains \( \frac{6Mbps}{2} = 3Mbps \) and $MT_2$ obtains \( \frac{54Mbps}{2} = 27Mbps \).
27Mbps). The power per bits transmitted is the same as the previous configuration
\(\frac{10W}{30Mbps} = 0.333 W/Mbps\).

The minimum power consumption is achieved in configurations 2 and 3 because only
one AP is powered on. However, the total data rate obtained in these cases is much
smaller in comparison to the first configuration and the power per bits transmitted
value is almost the double.

4. In the fourth configuration, \(MT_1\) is associated with \(AP_2\) and \(MT_2\) is associated with
\(AP_1\). Thus, \(MT_1\) both MTs obtain a data rate of 6 Mbps. In this configuration,
both APs are powered on, having a power consumption of 20W (10W per AP),
the total data rate is 12 Mbps, and the power per bits transmitted is \(\frac{20W}{12Mbps}\) =
1.66 W/Mbps. This case represents the worst possible configuration in terms of
energy consumption and data rate offered. The reason is that this solution achieves
the maximum power consumption and the minimum total data rate at the same
time. Moreover, it also results in the maximum power over throughput across all
configurations.

Table 3.1 summarizes the results obtained:

<table>
<thead>
<tr>
<th>(MT_1)</th>
<th>(MT_2)</th>
<th>Power[W]</th>
<th>Total Data Rate[Mbps]</th>
<th>Power/Throughput[W/Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(AP)</td>
<td>RATE</td>
<td>(AP)</td>
<td>RATE</td>
<td>20</td>
</tr>
<tr>
<td>1) (AP_1)</td>
<td>54</td>
<td>(AP_2)</td>
<td>54</td>
<td>20</td>
</tr>
<tr>
<td>2) (AP_1)</td>
<td>27</td>
<td>(AP_1)</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>3) (AP_2)</td>
<td>3</td>
<td>(AP_2)</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>4) (AP_2)</td>
<td>6</td>
<td>(AP_1)</td>
<td>6</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3.1: Data of the possible WLAN configurations

In addition, for the sake of making a complete analysis of this wireless network scenario
in terms of energy consumption and data rate offered, we analyse the possible states of the
previous wireless network scenario. A state is represented by \([x,y]\), the x axis represents
the total data obtained, and the y axis represents the total energy consumption. It is
important to mention that in figure 3.2 values have been normalized. In particular, in the y axis about energy consumption, an inverse normalization has been made, being 1 the minimum possible value and 0 the maximum possible value. Consequently, 0 represents the value 20W, and 1 represents 10W. The purpose of this analysis is to identify all details for the model design. In this example, it is assumed that both MTs are using the same MCS.

Figure 3.2: Possible states of the scenario

Figure 3.2 shows possible states for this scenario, the different states are:

1. \([0, 10]\): This state represents the scenario situation when only one AP is powered on and none of the mobile terminals are associated to it. The minimum power consumption of this scenario is reached in this state, and one AP is always required in order to support new MT associations.

2. \([6, 10]\): This state can be reached though two different scenario situations:

   - One AP is powered on, and only one MT is associated with it. This MT is located at the farthest distance within the coverage area, obtaining the minimum data rate.
• Both MTs, located at the farthest distance within the coverage area of the same AP, are associated with it, sharing the channel.

3. [30, 10]: This state represents the situation when both MTs, one of them located at the farthest distance and the other located at the closest distance within the coverage area of the same AP are associated with it. Since the channel is shared, MTs obtain the half of the achievable data rate.

4. [54, 10]: This state can be reached through two different situations:

• Only one AP powered on is providing connection to both MTs located in the closest distance within the coverage area of it, sharing the channel.

• Only one AP powered on is providing connection to one MT located in the closest distance within the coverage area of it, thus this MT obtains the maximum channel capacity.

5. [0, 20]: This state is reached when two APs are powered on, and no mobile terminal is associated with them. The system will avoid this situation in order to avoid wasting unnecessary energy because no user is associated.

6. [6, 20]: This state can be reached though two different situations of the scenario. They have in common that both APs are powered on:

• Both MTs are associated with the same AP. These MTs are located at the farthest distance within the coverage area of this AP. Thus, MTs are sharing the channel, obtaining the half possible data rate.

• Only one MT is associated with one AP, the MT is located in the farthest distance within the coverage area of this AP and it obtains the maximum channel capacity for this coverage area.
The system will avoid this situation too, switching off the AP that is not used, leading to the state \([6, 10]\).

7. \([12, 20]\): This state can be reached when both MTs are associated with both APs. Each MT is associated with a different AP. MTs are located at the farthest distance within the coverage area of each AP, obtaining the minimum data rate for each coverage area.

8. \([30, 20]\): In this state both APs are powered on but both MTs are associated with only one AP. The first MT is located in the closest distance and the other in the farthest distance within the coverage area of the same AP. The system will avoid this situation too, it is better to switch off the AP that is in idle state. Thus, the system will go to state\([10, 30]\).

9. \([54, 20]\): In this state, both APs are powered on, but there are two different possible situations to reach this state:

   - In the first situation, both MTs are located at the closest distance within the coverage area of one AP, sharing the channel.
   - In the second situation, only one MT, located at the closest distance within the coverage area of one AP, is associated with it, obtaining the maximum data rate capacity.

This state will be avoided also by the system, switching off the AP that is not in use, leading to the configuration of the state \([54, 10]\).

10. \([108, 20]\): In this state, both APs are powered on, and both MTs are associated with them. Each MT is associated with one different AP, and these MTs are located in the closest distance within the coverage area of each AP, obtaining each one the maximum data rate for each AP.
The next diagram represents the states that the system will avoid. It has the target of reducing the energy consumption through switching off APs when they are not necessary:

![Diagram of states avoided by the system](image)

Figure 3.3: States avoided by the system in this scenario

### 3.2 Model

In this section, we analyse the key factors that condition the performance of our mathematical model in terms of energy savings in dense WLAN deployments. Furthermore, based on this analysis, several assumptions to build the mathematical model will be established.

A wireless network is composed of many devices. However, the main elements that are relevant in this study are: access points, switches and mobile terminals.
The first important element in this study is the AP; each AP is connected to the Internet with a connection of capacity B. In order to manage a group of APs, it is possible to form a group of nearest APs called Wireless Cluster [23]. Wireless network scenarios can have regions with no coverage, but APs belonging to the same cluster can provide overlapping coverage. Thus, since the coverage area of APs that belong to the cluster are overlapped, the problem of regions with no coverage can be solved.

Clusters management can condition energy savings. Two types of management will be considered: distributed management and central management. If a distributed management is adopted, each AP manages itself individually. Thus, this management has an issue since it will be more difficult to share information among APs regarding the current number of MTs and the traffic load. However, if a central management is adopted, it is possible to have a single WLAN controller that manages all APs. Thus, the information about the
global state (number of users and traffic load) of the WLAN is available to the controller at any given time. This controller takes decisions about which APs will be switched on/off based on the global state, ensuring coverage to all users and achieving energy savings if it is possible.

The power consumption of APs must be considered too. APs power consumption is established based on the information obtained about energy requirement for CISCO, ARUBA and MERU access points, as it is shown in table 2.1. We assume an average value for APs energy consumption regardless the state in which APs are.

Another important feature to be considered is the Resource on Demand (RoD) policy used to switch on/off APs. In order to establish an effective RoD policy, defined in section 2.1, we need to establish several rules to choose the most suited for this problem, in the same context that [11]:

1. WLAN coverage must be maintained.

2. Quality of Service offered must not be reduced less than an established threshold.

3. WLAN operations must offer stability.

4. At least one AP remains active in the entire area served by the WLAN.

5. Avoid frequent re-associations to APs, caused by the switch off of APs.

In this context, two different RoD policies are considered: association based policy and traffic based policy. According to the analysis in section 2, since we need an effective RoD policy depending on the users location and the generated traffic, we adopt the traffic based policy. Through this policy, MTs that are not only associated with APs, but are in addition generating traffic will be taken into account. By using this policy, we take into account data rate variability, which means that if the number of MTs generating traffic
increases, it will be necessary to increase the number of APs powered on to maintain the QoS offered to end users.

In consequence, on the basis of offering the agreed minimum data rate, we make a comparison between the energy consumption when all APs are powered on and the energy consumption when the RoD policy is applied. In addition, we will study the total energy consumption versus the throughput obtained, considering the number of powered on APs and trying to maximize the ratio Mbps/W.

The second element is the switch. It connects the different APs between them, and it works as a bridge to the Global Network. Each AP is connected to a certain port of one switch, providing connection to the WLAN to MTs and providing communication between APs and MTs, according to the given definition in the section 2.1. Thus, switches represent the end point of the wireless connection with another IT-system.

The third important element for this mathematical model is a mobile terminal. There are important factors that must be considered in relation with this element:

- A mobile terminal can suffer a temporary disruption due to handovers. Handover refers to the process of transferring the service of one AP to another AP due to different reasons:

  1. It can be caused when the cluster controller decides to switch off certain APs in order to achieve energy savings. These APs can have some MTs associated with them. Consequently, these MTs must be re-associated with different APs to obtain connectivity.
  2. It also appears in a dynamic scenario, when a MT that is moving away from
the covered area of the AP that supports it. Consequently, in order to maintain the quality of service, the MT must be re-associated with another AP.

- During high traffic periods, the association and dissociation rate is high because many users are connecting and disconnecting to the WLAN. This phenomenon especially appears in public WLANs like a train station. Therefore, this variability must be considered to know the time interval at which the algorithm deciding which APs will be switched off must be executed, but this fact is not considered in our mathematical model.

In addition, in relation to this element the following assumptions are made:

- Since we assume a static scenario, we will not take into account handovers due to mobility of MTs. Handovers will be considered only when an AP is switched off, and the possible MTs that were associated with it must be re-associated.

- MTs are not equally associated with the available APs. Since MTs are randomly distributed in the scenario, the number of MTs associated to an AP may vary. In order to guarantee a certain QoS to MTs, regardless of the AP with which they are associated, a maximum number of MTs that can be associated with a certain AP will be considered in our model. Thus, if a certain MT tries to establish an association with an AP that has reached the maximum value, this AP will reject the connection and the MT will try to establish an association again with another distinct AP.

Once the analysis of the elements that compose the wireless network is finished, the next step is to develop the mathematical model. To do that, we need to identify and define the parameters and variables that represent these elements, their states, the existing relations between them and their behaviour based on the existing restrictions in the scenario.
These parameters, variables and constraints can be deduced through the basic information of the model and the previously defined elements.

We have decided to name the **parameters** with upper-case. Our parameters are:

- **Access Points**: APs are distributed in a given area, a set of $n$ APs is represented by $A$.
  \[ A = \{a_1, a_2, ..., a_n\} \] (3.1)

- **Mobile terminals**: MTs are distributed in a given area, a set of $m$ MTs are represented by $M$.
  \[ M = \{m_1, m_2, ..., m_m\} \] (3.2)

- **Power consumption**: we assume a constant power consumption for all APs. This power consumption is independent of the state in which the AP is (idle or receiving/transmitting) [11]. Thus, the set of power consumptions of APs is represented by $P$, as an example, $p_n$ is the power consumption of the $AP_n$.
  \[ P = \{p_1, p_2, ..., p_n\} \] (3.3)

- **Data Rate**: the possible data rate achievable by a MT, $m_i$, through an association with an AP, $a_j$, will be represented by $c_{ij}$. Thus, we represent all possible associations between MTs and APs by a set $C$.
  \[ C = \{c_{11}, c_{21}, ..., c_{mn}\} \mid \forall i \in \{1...m\}, \forall j \in \{1...n\} \] (3.4)

**Variables** will be represented with lower-case letters. These variables have been obtained through an analysis of the previous parameters of this mathematical model.
• **AP state:** the state of an AP is represented through the variable $s_i$, i.e. $s_i$ is the state of the AP $a_i$. If the AP is powered off, the state has the value 0. If the AP is powered on, the state has the value 1.

\[
s_i = \begin{cases} 
1 & \text{if } a_i \text{ is on} \\
0 & \text{otherwise}
\end{cases} \quad \forall i \in \{1\ldots n\}
\] (3.5)

• **Associations between MTs and APs:** a variable to represent the potential association of a MT with an AP is necessary. The term potential association is used because if a MT is out of the coverage offered by an AP, this MT cannot be associated with this AP. This relation is represented with the variable $u_{ij}$. It denotes that a MT, $m_i$, is associated or not with an AP $a_j$.

\[
u_{ij} = \begin{cases} 
1 & \text{if the MT } i \text{ is associated with the AP } j \\
0 & \text{otherwise}
\end{cases} \quad \forall i \in \{1\ldots m\}, \forall j \in \{1\ldots n\}
\] (3.6)

• **Data rate between a MT and an AP associated:** another value that we need to represent is the data rate obtained if there is an association between a MT $m_i$ and AP $a_j$: It is represented by $r_{ij}$. In this case we want to represent the data rate that a MT, $m_i$, obtains from an AP, $a_j$, as long as $m_i$ is associated with $a_j$. Of course, we must also satisfy the previous condition, i.e. for $m_i$ to be associated with $a_j$, the $u_{ij}$ value must be 1. If this condition is not satisfied the data rate obtained is 0.

\[r_{ij} \in \mathbb{R}_0^+ \quad \forall i \in \{1\ldots m\}, \forall j \in \{1\ldots n\}
\] (3.7)

Once the parameters and variables are defined, we identify the possible relations between them. Thus, we set up **constraints** for our variables.
• A MT only can be associated with one AP at any given point in time.

\[ \sum_{j=1}^{n} u_{ij} = 1 \quad \forall i \in \{1...m\} \]  
(3.8)

• Only \( x \) users can be associated with one AP.

\[ \sum_{i=1}^{m} u_{ij} \leq x \quad \forall j \in \{1...n\} \]  
(3.9)

• The sum of all MTs that are associated to a certain powered off AP, has to be 0.

\[ \sum_{i=1}^{m} u_{ij} < M \times s_j \quad \forall j \in \{1..n\} \]  
(3.10)

Formula 3.10 is interpreted as follows: for a given AP \( a_j \), if its state \( s_j \) is 0 then the sum of all MTs associate with it has to be 0. The variable \( M \) is set using the Big M Method which is used for solving linear programming problems. This variable refers to a large number associated with the artificial variables [19].

• A MT \( m_i \) can establish an association with an AP \( a_j \), obtaining a certain data rate if they are associated between them.

\[ r_{ij} \leq M \times u_{ij} \quad \forall i \in \{1...m\}, j \in \{1...n\} \]  
(3.11)

• The data rate obtained by a certain association between a MT \( m_i \) and an AP \( a_j \) has to be less or equal than the channel capacity that \( a_j \) has. The capacity could be shared if more MTs are associated with \( a_j \). Therefore, generalizing this case, the total data rate that a set of MTs obtains by being associated with a specific AP has
to be less or equal than the total bandwidth offered by this AP.

\[
\sum_{i=1}^{m} \frac{r_{ij}}{c_{ij}} \leq 1 \quad \forall j \in \{1...n\} \tag{3.12}
\]

- The data rate offered must be distributed between the MTs associated with APs depending on the value of the constant \(\gamma\), building in this sense a fair system.

\[
\sum_{k=1}^{n} \frac{r_{ik}}{c_{ik}} \times \gamma \geq \sum_{k=1}^{n} \frac{r_{jk}}{c_{jk}} \quad \forall i, j \in \{1...m\} \tag{3.13}
\]

Once the analysis to obtain the parameters, variables and constraints is finished, we compute and analyse the energy consumption on a given WLAN deployment. However, we have not defined the optimization objectives yet. Two key parameters are considered to establish the objectives, the total data rate obtained and the total power consumption.

One objective is to get the best network configuration in order to maximize the throughput obtained, achieving the maximum total data rate value. This parameter is denoted as \(F_0\). The total data rate is given by:

\[
F_0 = \sum_{i=1}^{m} \sum_{j=1}^{n} r_{ij} \tag{3.14}
\]

The previous objective conditions the other objective which is about the power consumption. We try to achieve the maximum throughput minimizing the total power consumption. This parameter is denoted as \(F_1\). The power consumption is given by the product of the power consumption of each AP with its state. Thus, it is computed only the APs that are powered on.

\[
F_1 = \sum_{i=1}^{n} p_i s_i \tag{3.15}
\]
Once we have defined the objectives to optimize, in order to offer a balance between energy consumption and data rate, the results obtained for each one will be contrasted. However, since for the objective about power consumption, the goal is to obtain the minimum value and for the objective about the total data rate, the goal is to obtain the maximum value, a conflict appears.

These two functions will compose the linear function that CPLEX will process. Therefore, it is necessary to establish the same criteria for both objectives. In order to solve this problem, for the parameter concerning to the total energy consumption, instead of minimizing this value, the minimum value for all scenarios experimented will be maximized. Hence, it is possible to process and contrast these two objectives through maximizing a linear function.

The final model to obtain the configuration which achieves an optimal balance between energy consumption and data rate is to maximize the linear function composed by the total power consumption of APs and the total data rate offered to guarantee a minimum coverage to end users subject to constraints (3.8) to (3.13).

3.3 Limitations and benefits

The limitations and benefits of this mathematical model will be presented in this section.

3.3.1 Limitations

We assume that the energy consumed by APs is constant for all states (10W). This is a limitation for real scenarios because APs have different energy consumption depending on their state (on/off) and model.

In addition, we consider a static scenario where MTs do not move. It does not repre-
sent a real situation because in real scenarios, mobile terminals could change their location frequently, changing the AP load and the position within the coverage area in which they are.

Another limitation is the large number of associations and disassociation in real scenarios. Consequently, the AP load changes frequently. It is also considered that MTs use the same modulation and coding scheme, obtaining the same proportion of data rate if the channel is shared. In a real scenario, MTs use different modulation and coding schemes, consequently, the data rate obtained will depend on the quality of the channel.

3.3.2 Benefits

The main benefit of this mathematical model is the energy savings achieved through switching off APs that are not necessary, considering users location, especially during low peak periods. In addition, the required QoS provided to end users is not dramatically affected for this purpose because we establish a minimum QoS that must be ensured by any possible solution.

In order to evaluate the effectiveness of the mathematical model, a cluster of 9 APs is considered. Within this cluster, it is possible to achieve energy savings of 30W (3 APs are switched off, considering a power consumption of 10W for each one) because only 6 APs are necessary to guarantee coverage to MTs. If this proportion is extrapolated to real dense WLAN deployments, composed by hundred to thousand APs, the energy saving achieved could be considerable. If the critical cost of energy is considered, the amount of money saved could be considered too.
3.4 Model implementation in CPLEX

As previously mentioned, we have used CPLEX to implement our mathematical model. CPLEX provides a fast way to build efficient optimization models and state of the art applications for the full range of planning and scheduling problems. Its Optimizer’s mathematical programming technology enables analytical decision support for improving efficiency, reducing costs, and increasing profitability.

According to [24], CPLEX provides flexible, high-performance mathematical programming solvers for linear programming, mixed integer programming, quadratic programming, and quadratically constrained programming problems. In particular, for this mathematical model, a linear function, composed by two objectives, must be maximized subject to a set of linear constraints over variables constrained to be non-negative and boolean variables. CPLEX has the perfect tools for this purpose.

In this section, the CPLEX files that compose the mathematical model are described. A .mod file is a file where it has been written the objectives and constraints and a .dat file is a file where it has been established the input data for the program.

In the .mod file, we first define a set of variables that will be read from the file that contains all the information about our wireless network scenarios: number of mobile terminals, number of APs and their power consumptions, the data rates that each MT can achieve being associated with the different APs, the maximum value of users that can be connected to one AP and the values for $\alpha$ and $\gamma$ and other information that will be shown. In order to define a variable in CPLEX that will take the value from one input file, it is necessary to use a specific format:

\begin{verbatim}
int ap = ...;
float p[i in 1..5] = ...;
float C[i in 1..5][j in 1..10] = ...;
\end{verbatim}
Then, a set of decision variables that the program will use to make the different combinations to obtain results is established. In this case, these variables are:

- The state in which the APs can be (0 or 1). It indicates if the AP is powered on/off respectively, defined in CPLEX as:

  \[ \text{dvar int state}[i \in 1..\text{ap}] \text{ in } 0..1; \]

  In our model, this variable corresponds to the variable \( s \) specified in (3.5).

- The association matrix, which represents the possible associations between the MTs and the APs. It is 1 if one MT is associated with an AP and 0 in other case.

  \[ \text{dvar int association}[\text{in } 1..\text{mt}][1..\text{ap}] \text{ in } 0..1; \]

  In our model, this variable corresponds to the variable \( u \) specified in (3.6).
• The data rate matrix, which represents the data rate that each MT can achieve being associated with different APs.

\[
dvar \text{float} + \text{dataRates}[\text{in 1..mt}][\text{1..ap}];
\]

In our model, this variable corresponds to the variable \( r \) specified in (3.7).

• The variable \text{objective1} represents the objective of this mathematical model about the data rate.

\[
dvar \text{float} \text{objective1};
\]

In our model, this variable corresponds to the variable \( F_0 \) specified in (3.14).

• The variable \text{objective2} represents the objective of this mathematical model about the energy consumption.

\[
dvar \text{float} \text{objective2};
\]

In our model, this variable corresponds to the variable \( F_1 \) specified in (3.15).

• The variable \text{normEnergy} represents the normalized \text{objective1} value.

\[
dvar \text{float} \text{normEnergy};
\]

• The variable \text{normRate} represents the normalized \text{objective2} value.

\[
dvar \text{float} \text{normRate};
\]

Ap represents the number of APs and \text{mt} the number of MTs.

The next step is to define the function that we want to maximize:

\[
\text{maximize } \alpha \times \text{normRate} + (1 - \alpha) \times \text{normEnergy} \tag{3.16}
\]
where we are going to apply values for $\alpha$ between from 0 to 1 in order to modify the importance of the two objectives, the bigger value of $\alpha$ the bigger importance to the data rate.

In addition, we will define the different constraints that our problem presents, as we explained in section 3.2. A template for programming these constraint in CPLEX is:

```latex
subject to {
  forall (i in 1..ap)
    sum(j in 1..mt) C[i][j];
}
```

In order to generate the .dat file, represented in figure 3.5, we implemented two Java programs. The first one generates the scenarios with a given number of MTs, APs and the distance between them. The second generates the input file for CPLEX based on the results of running the first program. For the input file we want to highlight that it contains the real value for all the previous variables defined as it is depicted in Figure 3.6.
In order to run the program and get possible scenarios, we must first establish the values for the equations which are used to compute the data rate achievable for each MT presented in section 2.1.

First of all, to calculate the log-distance path loss model through the Formula 2.1, we establish $n = 4$ and $d_0 = 10$. In order to calculate the Freespace Path Loss through the Formula 2.2 we establish the frequency value for WLAN as $2.4 \times 10^9$. In order to calculate the receiver power through the Formula 2.3 we establish $T_x = 20dB$. Finally to calculate the signal to noise ratio in decibels through the Formula 2.4, based on [25], according to Figure 1.18, we establish $P_{\text{noise, dB}}$ to 95. If 802.11b is used, the allowable Interference Level (dBm) is -105.4 dBm. If De-sensitization offset is not considered, the overall noise floor of the receiver is -95.4 dBm.

With the SNR values we need to calculate the data rate in terms of SNR. We obtained...
it based on table 3.2, by this way we can achieve the final values for data rate:

<table>
<thead>
<tr>
<th>SNR(dB)</th>
<th>Distances (m)</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x &lt; 8$</td>
<td>$d \geq 13$</td>
<td>0</td>
</tr>
<tr>
<td>$8 \leq x &lt; 9$</td>
<td>$12.52 &lt; d \leq 13$</td>
<td>6</td>
</tr>
<tr>
<td>$9 \leq x &lt; 11$</td>
<td>$11.59 &lt; d \leq 12.52$</td>
<td>9</td>
</tr>
<tr>
<td>$11 \leq x &lt; 13$</td>
<td>$10.74 &lt; d \leq 11.59$</td>
<td>12</td>
</tr>
<tr>
<td>$13 \leq x &lt; 16$</td>
<td>$9.57 &lt; d \leq 10.74$</td>
<td>18</td>
</tr>
<tr>
<td>$16 \leq x &lt; 20$</td>
<td>$8.2 &lt; d \leq 9.57$</td>
<td>24</td>
</tr>
<tr>
<td>$20 \leq x &lt; 24$</td>
<td>$7 &lt; d \leq 8.2$</td>
<td>36</td>
</tr>
<tr>
<td>$24 \leq x &lt; 25$</td>
<td>$6.77 &lt; d \leq 7$</td>
<td>48</td>
</tr>
<tr>
<td>$x \geq 25$</td>
<td>$d \leq 6.77$</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 3.2: Minimum SNR required to obtain a given Data Rates and distances

The next step to run the program, is to change the $\alpha$ value. We have defined a script to do this automatically, making it possible to interact with the model and solving several instances of it, in particular we have named it main.mod.

We have made also another .mod file to be called by the main.mod file in order to compute the best possible solution within the range of different solutions obtained through the different values of $\alpha$. 
4 Evaluation

4.1 Scenario Description

In this section, we analyse and evaluate different scenarios in order to determine the effectiveness of our work in dense WLAN deployments.

Through the previously explained Java program, we have generated a set of clusters of APs in a square area. The positions of the APs are evenly distributed in the simulation area. Thus, the number of APs must have a perfect square. MTs are located randomly in the scenario, avoiding the possibility of being located in the same coordinates as APs. We have analysed a simple cluster, extending the conclusions to large WLAN deployments.

The energy consumption of APs is fixed to 10W regardless of the state in which they are. We have considered this assumption in order to develop a general flexible mathematical model, capable of adapting to actual dense WLAN deployments. However, this is not a realistic assumption because in real scenarios, APs have different energy consumptions depending on their state. Table 2.1 depicts that APs produced by Meru in idle state consume less than in a receiving or transmitting state. In fact, our model takes into account the possibility of having different energy consumptions for each AP, but it takes into account only the static energy consumption of each AP.

We describe and analyze three different scenarios in the following section. All the analysed scenarios are represented in figures 4.1, 4.2 and 4.3. They show the distribution of APs and MTs, as we vary the distance between APs from 10 to 25 meters. The blue diamond points represent APs and the red squares represent MTs.
Figure 4.1: Scenario with distance between APs of 10 meters

Figure 4.2: Scenario with distance between APs of 17 meters
4.2 Performance Evaluation

We evaluate in this section the results obtained by varying the distance between APs (10, 17 and 25 meters). Particularly, we compare the impact of varying the distance between APs on the two objectives considered by the mathematical model. As was previously defined, the two objectives are: to maximize the total data rate offered and to minimize total energy consumption. We also study the influence of the parameter $\alpha$. This parameter determines the relative importance of both objectives on the final performance. In particular, for low $\alpha$ values, the importance is on the reduction of energy consumption, whereas for high values the importance is on the increase in data rate. We set $\gamma$ value to 5 in order to guarantee the distribution of the total data rate among MTs.

In figures 4.4, 4.5, 4.6, the x-axis represents the different values for $\alpha$, from 0.1 to 0.9. The right y-axis represents the total data rate obtained by MTs in megabytes per second.
for each value of alpha. The left y-axis represents the total power consumption of APs in Watts for each value of alpha.

Figure 4.4 focuses on the scenario in which APs are separated by 10 meters. The best results in terms of energy consumption are obtained for low values of alpha (see red line). When $\alpha$ increases, the energy consumption has less importance, and then the data rate obtains the highest values (blue line). In this regard, in order to reach the maximum value in terms of data rate, 9 APs are required to be switched on. We can see there is an inflexion point when alpha is close to 0.5, i.e. both objectives have the same importance.

![Alpha vs Data Rate & Energy Consumption (d = 10m)](image)

Figure 4.4: Comparison of objectives vs. alpha, with distance between APs of 10 meters

If the distance between APs is increased to 17 meters, there is a similar behaviour as we show in figure 4.5. Due to this separation, APs cannot offer the same data rate offered than in the previous scenario, despite the coverage area being bigger. Thus, the total data
rate offered decrements from 482.4 Mbps to 408.6 Mbps. In fact, 9 APs are still necessary to obtain the maximum total data rate value.

Figure 4.5: Comparison of objectives vs. alpha, with distance between APs of 17 meters

If the distance between APs is increased to 25 meters as we show in figure 4.6, MTs obtain a total data rate that decreases from 408.6 to 237.6 Mbps. In addition, the QoS offered to MTs could be worse because of the distance between MTs and APs being bigger. That means more possibilities of packet losses, etc. Furthermore, if the separation between MTs and APs is increased, the overlapping coverage almost disappears, and MTs associations with APs cannot vary as much as in previous scenarios with a lower separation.

There are shared conclusions for figures 4.4, 4.5 and 4.6. Towards achieving high total data rate offered values, it is necessary to increase the number of APs powered on. In consequence, the total power consumption increases.
Figures 4.7 and 4.8 show the impact of the number of MTs on the total offered data rate and the total power consumption for different values of $\alpha$. The x-axis represents the number of MTs considered, ranging from 0 to 15. The y-axis represents the total data rate offered to users in megabytes per second in figure 4.7 and the total power consumption in Watts in figure 4.8. To obtain reliable results we have generated 30 scenarios for each number of MTs, obtaining a total of 90 scenarios. For all these scenarios a distance between APs of 10 meters and different location distributions of MTs for each scenario are considered. Each point in figures 4.7 and 4.8 represents the average of all values obtained for value of $\alpha$. We also show the standard deviation for all of them, represented by whiskers with the same colour of the point.

Figure 4.7 shows the variability of the total offered data rate for each number of MTs.
In this context, three different values for $\alpha$ are considered: If $\alpha$ has the value 0.1, the total data rate offered has minor importance and the most important objective in this case is the total energy consumption. As $\alpha$ is incremented, the objective of the total data rate gets more importance. In addition, if the number of MTs increases, we need to increase the total data rate offered in order to support all of them. That means sacrificing the total energy consumption.

![MTs vs Data rate](image)

Figure 4.7: Impact of MTs number on the data rate

Figure 4.8 shows the impact of the number of MTs on the total energy consumption. If $\alpha$ has the value 0.1, the maximum weight is on the total energy consumption. It is interesting to point out that for 15 MTs just 3 APs are powered on. If we increment the number of users from 5 MTs to 15 MTs, we can see that the increment in terms of energy consumption is proportional to one AP for each 5 MTs. The two next cases, for $\alpha = 0.5$ and $\alpha = 0.9$, are not like this. In fact, the energy consumption does not increase
at the same rate as the number of MTs. There is a fast growth from 5 MTs to 10 MTs and from 10 MTs to 15 MTs it is only necessary one more AP.

Figure 4.8: Impact of MTs number on the Energy Consumption

Based on these figures we can conclude that in order to support more MTs, it is necessary to power on more APs due to the fact that an increment of the total data rate is required if we do not want to sacrifice the data rate.

We analyse different possible configurations for the different scenarios in order to choose the best one in terms of total energy consumption and total offered data rate. Figures 4.9, 4.10 and 4.11 confront the total data rate against the total power consumption to obtain different configurations and choose the best option. The x-axis represents the total data rate offered to MTs in megabytes per second, from 0 to 600. The y-axis represents the total power consumption in Watts, from 0 to 100. In these figures a Pareto frontier has
been built, giving different values for $\alpha$. In addition, it has been calculated the utopia point giving the maximum value for the total data rate and the minimum for total power consumption. For $\alpha$ equal to 1, the maximum total data rate offered is obtained and for $\alpha$ equal to 0, the minimum total power consumption is obtained. Therefore, the best option is the closest point contained in the Pareto frontier to the utopia point.

Figure 4.9 compares the total data rate and total energy consumption in a scenario with 10 meters of distance between APs, the utopia point is situated at [482.4, 30]. In this plot, three points are calculated: [150.23, 30], [320.4, 60], [482.4, 90]. According to our mathematical model the best result in this case is [320.4, 60] because it is the closest point to the utopia point in terms of total energy consumption and total data rate offered.

Figure 4.9: Data Rate vs. Energy Consumption with distance of 10 meters between APs

Figure 4.10 shows the total data rate versus the total energy consumption in a scenario
with 17 meters of distance between APs. In this case, varying the value of $\alpha$, three points are calculated: [119.53, 30], [286, 60], [408.6, 90]. The utopia point is situated at [408.6, 30]. According to our mathematical model the best result in this case is [286, 60] because it is the closest point to the utopia point in terms of total energy consumption and total data rate offered.

![Data Rate vs Energy Consumption (d = 17m)](image)

Figure 4.10: Data Rate vs. Energy Consumption with distance of 17 meters between APs

Figure 4.11 shows the total data rate versus the total energy consumption in a scenario with 25 meters of distance between APs. Varying the value of $\alpha$ again, different points are calculated: [88.62, 30], [128.67, 40], [189, 60], [228, 80], [237.6, 90]. The utopia point is situated at [237.6, 30]. According to our mathematical model the best result in this case is [189, 60] because it is the closest point to the utopia point in terms of total energy consumption and total data rate offered.
Figure 4.11: Data Rate vs. Energy Consumption with distance of 25 meters between APs

Once all the configurations have been studied, we show in table 4.1 a summary about relevant data and calculations. Furthermore, we show the percentage of energy saved and the possible capacity which is lost with these energy savings.

<table>
<thead>
<tr>
<th></th>
<th>10m</th>
<th>17m</th>
<th>25m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC (W)</td>
<td>DR (Mbps)</td>
<td>PC (W)</td>
</tr>
<tr>
<td>Utopia point</td>
<td>30 482.4</td>
<td>30 408.6</td>
<td>30 237.6</td>
</tr>
<tr>
<td>Maximum</td>
<td>90 482.4</td>
<td>90 408.6</td>
<td>90 237.6</td>
</tr>
<tr>
<td>Result obtained</td>
<td>60 320.4</td>
<td>60 286</td>
<td>60 189</td>
</tr>
<tr>
<td>%</td>
<td>66.66</td>
<td>66.14</td>
<td>66.66</td>
</tr>
<tr>
<td>% saved</td>
<td>33.34</td>
<td>33.86</td>
<td>33.34</td>
</tr>
</tbody>
</table>

Table 4.1: Results, **PC**: power consumption(W), **DR**: data rate(Mbps)

According to the obtained results, we can see that energy savings and the total data rate offered, have almost a linear behaviour. In all previous analysed scenarios, it is possi-
ble to achieve energy savings of 33.34% losing around 33.86%, 30.01% and 20.46% of the total data rate offered in scenarios with 10, 17 and 25 meters between APs respectively. As an average value, it is possible to achieve a 33.34% of energy savings, sacrificing around the 28.11% of the total offered data rate.

In a scenario with 9 APs, the energy saving is acceptable. However, if we consider a dense WLAN deployment composed by 450 APs, grouped into clusters of 9 APs, 50 clusters will be formed. If the energy savings for clusters formed by 9 APs are applied, saving 30W in each one, an energy saving of 1500W in total is obtained, i.e. for a total of 450 APs inside the dense WLAN deployment, only 300 APs are required to guarantee a good QoS, making it possible to switch off 150 APs.

Figure 4.12 shows the evolution of $\gamma$. With this parameter, we distribute the available data rate among the MTs in the scenario, avoiding that a MT receives 0 Mbps if it can obtain certain data rate, although another MT must receive less data rate. The x-axis represents the value of $\gamma$ ranging from 0 to 3.5 and the y-axis represents the total data rate in megabytes per second, ranging from 0 to 600. The $\gamma$ variable only influences the total data rate according to the equation 3.13. To focus on the total data rate, we set $\alpha$ to a value of 1. We get five points which indicate that for larger values of $\gamma$, higher values for the total data rate are obtained.
Figure 4.12: Scenario with distance between APs of 15 meters

This increase in the total data rate is caused because $\gamma$ enforce our program to select higher values among the possible data rates that a MT can obtain. $\gamma$ should be greater of 0 to ensure a distribution of the total data rate. Large values of $\gamma$ should be set to assign a minimum QoS to the farthest MTs in the coverage area. A good value of $\gamma$ depends of the number of MTs in each clusters, because a large number of different combinations of data rates to assign to MTs are possible.
5 Summary and Conclusion

In this document we have analysed the structure and the energy consumption of dense WLANs deployments. Such deployments need to adapt their performance to support user demands which may be particularly strong, especially after the growing use that wireless mobile terminals have experienced. In addition, recently users require even higher data rate than a few years ago. This is mainly due to the fact that modern applications, especially video streaming applications, pose stronger requirements in terms of delay, bandwidth and so on.

The need to offer more data rate is solved by adding more APs to actual WLANs deployments. However, this is not a sustainable model of growth in terms of energy consumption since APs are powered on at all time in order to provide connectivity to users. Thus, it is necessary to consider that some APs are not needed at certain moments.

Consequently, a balance between the total energy consumption and the total data rate offered needs to be achieved. This is not a simple task because there is a conflict between these two objectives. On the one hand, in order to provide a higher total data rate, it is necessary to increase the number of powered on APs. On the other hand, in order to achieve energy savings, the total data rate offered has to be sacrificed by powering off some APs.

Given that there are low peak traffic periods where it is not necessary to have all APs powered on (e.g. at night), we have designed a mathematical model that allows us to compute possible configurations to achieve energy savings through switching off APs that are not necessary.

The mathematical model in this work is based on the idea of a centralized network
management, which allows one device to know the global state of the network, giving the possibility to choose APs that can be switched off based on the number of users that are generating traffic. Furthermore, we assume that each AP has an energy consumption of 10W, and APs will be grouped into clusters in order to make their management easier.

In particular, in our study, a scenario composed of 9 APs located in a square area where mobile terminals are randomly placed is considered. We study different distances between APs so that we can validate the performance of our solution under different sets of scenarios. Our results show that we can achieve energy savings in all scenarios without dramatically sacrificing the data rate offered to end users.

For example, considering a scenario composed of 9 APs, each cluster has an energy consumption of 90W. If our proposed solution is applied to this scenario, through studying different distances between APs, the average power consumption of the cluster is reduced by around 33.34%, sacrificing an average of 28.11% of the total data rate offered. As a result, a good balance between total energy consumption and the total data rate offered can be achieved.

Regarding the limitations of our model, we set the power consumption of APs to 10W. This is not a realistic assumption since different AP models are not being considered. Another limitation is that we consider a static scenario where users are not allowed to change their position. In addition, we assume that all users are employ the same modulation and coding scheme, obtaining the same proportion of data rate if the channel is shared. In a real scenario, users can use different modulation and coding schemes. As a result, the data rate obtained that they obtain depends on the quality of the channel.

For future work, it would be convenient to develop a model considering dynamic sce-
narios, i.e. it is necessary to take into account that users are constantly moving around the scenario causing a lot of associations and disassociations, especially in public WLANs. Also we need to consider that during a day, different number of users are active and have different and varying traffic demands.
References


