Wireless LAN planning: a didactical model to optimise the cost and effective payback

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Abstract: The Wireless Local Area Networks (WLAN) large-scale deployment is a difficult parameterisation work and it requires an automatic planning process with formal models. This paper proposes a solution to this matter and provides a model integrating all useful parameters to estimate the location and parameter settings of such network while optimising network costs and throughput. The access point location, the access point pattern, the antenna orientation, the emitted power and the antenna frequency channel are set in this model which brings together cell and frequency planning features (mix of Automatic Cell Planning (ACP) and Automatic Frequency Planning (AFP) problems).

With the formal model description this paper illustrates step by step the process of WLAN planning from the AP location to the effective throughput computation. A fair example is given at each section to didactically emphasise the planning problem and the model we defined. At the end, the optimisation problem is to minimise the economical cost of deployment and the economical cost of throughput loss inside a unique and understandable objective function.

Keywords: optimisation model; wireless planning; IEEE 802.11 WLAN.


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1 Introduction

Wireless Local Area Networks (WLAN) allow its users to benefit from the usefulness of Ethernet Networks and add mobility and flexibility being freed from the need for connecting itself physically to the network through a wire. The emergence of the IEEE 802.11 standards by the end of the 1990s has provided a common framework for the WLAN development (IEEE 802.11, 1999). Now this framework has contributed to the success of this new kind of radio access to data networks since 2000 and will probably reach $5 billion in 2006 worldwide market (ZDNET, 2005).

Initially, the design of such networks was done without predefined rules, but rather with some designers’ intuition. The increased number of users in these networks and the deployment need on large scales has led to complex network configuration problems requiring adapted solutions. Designers are no longer able to conceive networks that satisfy economical and technical constraints in time. Also wireless operators become very sensitive to the economical challenges of WLAN and they require rapid solutions to more and more sophisticated context such as outdoor coverage, 3D indoor coverage, multiserive networks, etc, to complete their 2G and 3G wireless cellular services from GSM, CDMA or UMTS mobile network layers.

Firstly the main task of WLAN designers is to determine the number, the location and the parameter settings of Access Points (name for WLAN transmitters) required for a full coverage of a given area; this task is well known in the literature as Cell Planning and is often referenced as a facility location problem. Secondly, they also have to assign the frequency channels to the different access points in order to provide the best throughput and then Quality of Service (QoS); this task is called Frequency Assignment and is a kind of graph colouring problem. Both tasks are usually tackled separately but they are hugely tied: the interference problems linked to cochannel and adjacent channels frequency reuse require the designer to tune the initial network, so to return to the cell planning task and to iteratively move from the Automatic Cell Planning (ACP) to the Automatic Frequency Planning (AFP) several times. To increase the complexity of the global design process, the designers must find solutions which are dedicated to a given traffic demands and which minimise some economical costs!

Literature provides a large variety of approaches dealing with the WLAN planning problem either on cell planning or frequency assignment or both. We will not investigate the works where only one problem was tackled because it is only a part of the WLAN planning and definitively both parts (ACP and AFP) cannot be separated to get good solutions as soon as the instances to solve are difficult. Indeed interference problem between frequency channels cannot be solved without considering that AP parameters settings or AP locations are also parameters of interference minimisation and throughput maximisation. So all problems, that is, finding AP locations, parameters and channels, are only one problem to get the best throughput. Nevertheless here are some of the works that propose solutions where both problems are managed as separated problems for different reasons (Amaldi et al., 2004a,b; Battiti et al., 2003; Glasser et al., 2005; Kamenetsky and Unbehaun, 2002; MacGibney and Klepal, 2005; Runser, 2005; Stamatelos and Ephremides, 1996; Unbehaun and Kamenetsky, 2003; Wright, 1998). Sometime the work was dedicated to a mathematical solving method for a specific problem such as in Amaldi et al. (2004b) where it was local search for facility location problem and sometime the work was more oriented on particular planning objectives such as coverage problem in Wright (1998). We would like to emphasise that this matter, that is, dealing with ACP and AFP separately or not, is not specific to WLAN and other works were also done on mobile networks like GSM, CDMA and UMTS. Amzallag et al. (2005), Hurley (2002) and Reininger and Caminada (2001) might be good starting point to look at the works done in those kinds of networks. Even if some ideas can be transposed from one problem to another one, among others there are two main difference distinguishing WLAN and mobile networks planning problems: problem instance size, which is much more bigger in mobile networks and throughput computation (from offered traffic and frequency channels assignment) which is much more complicated in WLAN.

Some works challenged WLAN ACP and AFP at the same time in more complex but realistic manners. In Rodrigues et al. (2000), Lee et al. (2002) and Mathar and Niessen (2000) reuse frequency constraints between all couples of sites are used to explain channel separation in order to avoid interference. Then the procedure consists in avoiding choosing sites for AP location, which are linked by reuse constraints. These works are based on graphs where nodes are the sites and edges link sites which cannot used the same frequency channel in Mathar and Niessen (2000) (edges are known as cochannel interference constraints) or cannot used cochannel and adjacent frequency channels with a minimum separation of three channels in Rodrigues et al. (2000) (edges are known as adjacent-channel interference constraints). Using this separation model (Lee et al., 2002) showed that this constraint-based approach is blocked when the offered traffic needs a lot of AP around the same place. In this case the AP choice is rapidly blocked by the reuse constraint graph. These approaches are not new as they come from other works done on cellular system. In this context (Hurley et al., 2000) showed that channel reuse constraints is not the only one solution. In addition to the blocking situation, the higher criticism on that way is that the constraints are only based on bilateral information between transmitters and it misses multiple interference problems, so the real throughput is always worst than the model estimation.

More recent ACP/AFP works without separation constraints in WLAN context were proposed in Ling and Yeung (2005), Bahri and Chamberland (2005), Wertz et al. (2004) and Prommak et al. (2002). The work initiated by Prommak et al. (2002) uses multiple interference computation as constraints: the sum of interfering signal in cochannel with a given signal must be lower than a given threshold. As well (Wertz et al., 2004) uses multiple
interference computation but includes it as criteria in the fitness function so the authors can tackle unsatisfied WLAN planning problem. None of these works use adjacent channels so interference evaluation is still optimistic; in Wertz et al. (2004) the matter is solved using only three non-overlapping channels of the total bandwidth. Solutions are then suboptimal. In Bahri and Chamberland (2005) the problem is to minimise the AP number while satisfying constraints on coverage and interference. This work is also based on multiple interference computation but the AFP part only uses non-overlapping channels, so multiple interference are cochannel based. Also the main purpose remains the coverage, as there is no offered traffic per client and traffic load on AP. Still based on three channels for AFP and cochannel multiple interference computation, Ling and Yeung (2005) also proposed a joint ACP/AFP where the main objective is to optimise the fairness between terminals by throughput balance. The authors use a specific throughput computation model to choose the AP to locate and the best channel for it. The network is built sequentially by adding successively the couples (AP, CH) until a predefined number of AP is reached then the algorithm returns its local minimum. Within all these recent approaches the AFP is still reduced to a limited choice of frequency channels that simplifies the interference computation matter and the problem combinatorial. But in the same way, it also considerably limits the potential of using adjacent overlapping channels in favourable context.

We propose to deal with this global ACP/AFP challenge with a global model that really overlaps both ACP and AFP problems. In fact we are not considering explicitly these problems as we focus on throughput optimisation on a list of Test Points (TPs) inside the area to cover. Then, sites, antennas and frequencies are components to compute the radio quality on a multiple interference context without any separation constraint and without explicit restriction on frequency reuse. Our computation of network evaluation is done on a single way from the received power to the real throughput, through the signal-to-interference ratio including all available frequency channels of the WLAN system and multiple interference computation. In addition to these global features we also bring additional features such as distinguishing the number of terminals for different demands, defining service zones inside building with different layers of priority and considering both network planning from green field and network expansion from one existing network, which are major issues in WLAN current deployment not used in existing formal models. It is also noticed that most of the time optimisation is carried out by considering only separated technical criteria; for example network coverage, cell overlapping, network capacity or network throughput. We consider that from the designer point of view all technical criteria must be transformed in economical gain or cost in regard to the cost of the network, the cost of the installation, the cost of throughput loss and the gain of clients. Then we define one economical fitness function as unique criterion including all costs and gains criteria linked to network deployment and traffic demand satisfaction.

In this context, the aim of this paper is to present a WLAN planning formal model which describes the whole problem parameters and which defines, in a precise way, an estimation of the economical cost and throughput of one network. Then, considering the problem of WLAN planning understanding, in this paper a case study is presented from the beginning to the end of the planning process involving all features of the mathematical model. The case study gives numerical computation on network samples. In this work, propagation data are considered as a problem input computed from any propagation modelling approach (Walke, 2002).

As explained before the WLAN planning difficulty raises essentially on two interlaced NP-hard problems: to select the best sites for AP location and to assign the frequency channels to each AP. We will deal with these two aspects simultaneously so that the model is not a succession of ACP and AFP subproblems but a real overlapping of both problems inside a unique fitness function computation. That makes it possible to guarantee the best optimisation of the network flow criterion, which is the most significant performance criterion for the customer. Doing this we will introduce new parameters on channels management with cell planning.

This paper is organised around the definition of problem variables and the description of network behaviour. Section 2 defines the AP location through data and variables linked to the sites and the sectors description. Section 3 defines the set of parameters of AP such as the frequency channels, the antenna patterns list, the antenna emitted power and the antenna azimuth. All these components are variables to assign. Then, the traffic model that describes the load requirements in the network and all QoS aspects are introduced in Section 4. And the throughput model that defines the evaluation of bit rates as well as the association rules between the clients and the AP is described in Section 5. Finally, the Section 6 defines the main problem to optimise.

2 AP location: candidate sites and sectors

In our model, a finite set of candidate sites is predefined. A site is a geographical location where an AP may be assigned. So the sites define places in the studied building. On each site, several AP may be installed to provide higher bit rates in strongly congested zones. Then we define the sectors as the list of available AP locations per site. This terminology is currently used in mobile network design (Reininger and Caminada, 2001). In this case, all site sectors share the installation cost for the site. Throughout this paper, the presented case study will be limited to a maximum of two sectors per site.

2.1 Model description

The following describes the variables for sites and sectors and then we plot a case study.

- $S$ set of candidate sites ($n^s = |S|$).
- $s$ indicates the $s$th candidate site with $s \in \{1, \ldots, n^s\}$. 
• $E$ set of available sectors (or available AP locations). Its site and its sector on this site characterise one AP location. $E = \{ e = (s, l) \in S \times L \}$ with $L = \{1, 2\}$, the set of available sectors on a site.

• $n^e$ total number of available sectors: $n^e = |E| = |S| \times |L| = n^s \times n^l$.

• $c^s_i$ installation cost of site $s$. It indicates any cost linked to the site: the site access difficulty, the cost of the wire connecting the AP to the LAN, etc.

• $E'$ set of sectors on which one AP is already installed ($n' = |E'|$). In a building, a set of AP may be already installed; it is an initial WLAN and in this case the aim of the planning is to expand it. These AP cannot be moved and their parameters cannot be modified. For such locations: $E' \subset E$.

• $S'$ set of sites on which one AP is already installed: $S' = \{ s \in S' \exists l \in L, (s,l) \in E' \}$ and $S' \subset S$. $\forall s \in S'$, $c^s = 0$ € knowing that these sites were already installed.

2.2 Case study of AP location

The following case study (Figure 1) is based on the description of one office building where six sites are defined and one AP is already installed in site 4 sector 1; so there are five green sites.

3 AP parameters setting

Once the AP location is set, it is necessary to determine which AP is suitable to be placed on sites and sectors from a given list. The AP must be chosen among manufacturer’s Equipment. When one AP is selected, we define its set of parameters that is, azimuth, emitted power and frequency channel. We state in this paper that one antenna radiation pattern is dedicated to each AP but it may be introduced as variable as well for AP with external antenna connection. In the case study presented to illustrate the model at the end of this section, the AP choice is limited to two Cisco’s AP with internal antenna.

3.1 Model description

This section firstly describes the sets of AP and frequency channels to assign; then it gives the list of parameters for AP and the decision variables.

• $A$ list of AP types ($n^a = |A|$).

• $a$ indicates the $a$th AP type, $a \in A = \{1, \ldots, n^a\}$.

• $F_a$ set of frequency channels used by the AP from $A$. This set varies depending on used standard: 802.11b/g or 802.11a. This model allows the planner to design 802.11b/g exclusive-or 802.11a networks. But we may introduce a dedicated list of channel per AP type to integrate all combinations of AP inside the same network.

• $F_a = \{1, \ldots, 13\}$ for IEEE 802.11b and 802.11g standards (list for Europe).

• $F_a = \{1, \ldots, 8\}$ for IEEE 802.11a standard (list for Europe).

• $n^a$ number of available frequency channels.

• $n^a = |F_a| = 13$ or 8 according to whether the $b/g$ or $a$ standard.

Figure 1  Case study of AP location
Each type of AP, noticed \( a \), has the following parameters:

- \( c_a \): purchase and installation cost of \( a \). This cost is independent of the site installation cost given in the previous section.
- \( r_a \): antenna radiation pattern of \( a \).
- \( H_a \): set of available azimuths for \( a \). The azimuth is expressed in degrees (°) and indicates the angle between the North and the antenna radiation direction in the horizontal plane. Azimuth sets are predefined for different antenna types. For example:
  - \( H_a = \{0°\} \) for omni-directional antennas.
  - \( H_a = \{0°, 45°, 90°, 135°\} \) for bi-directive antennas.
  - \( H_a = \{0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°\} \) for other directivity antennas.
- \( n^H_a \): number of possible azimuth values for \( a \):
  \[ n^H_a = |H_a| \leq 360. \]
- \( P_e \): set of emitted powers for \( a \). The power is expressed in dBm (decibels per milli-watt). A set of power values is given in accordance to manufacturers engineering rules. For example:
  - \( P_e = \{5, 10, 15, 20\} \).
  - \( g_a \): gain of \( a \) expressed in dBi
  - \( b_a \): standard (IEEE 802.11b/g/a) used by \( a \).

Then, four decision variables are defined on AP:

1. \( w_a \): indicates the type of AP installed at location \((s, l)\):
   \[ w_a \in \{A \cup \emptyset\}. \]
   \( w_a = a \) if the location \((s, l)\) is chosen to install one AP of type \( a \)
   \( w_a = 0 \) if \((s, l)\) location is unoccupied.

It is deduced that:

- \( n^a \): the number of AP located on the site \( s \). Knowing that it is limited to two AP per site in our proposal but it may be extended: \( n^a \in L \cup \{0\} = \{0, 1, 2\} \).
- \( E^s \): subset of chosen locations for AP. One chosen location is defined by one site and one of its available sectors.
  \[ E^s = \{(s, l) \in S \times L / w_a \in A\} \]
  \[ E^s = \{(s, l) \in S \times L / w_a \neq 0\} \]
  with \( E^s \subset E \) and \( E^s \subset E^s \).

- \( n^s \): number of chosen locations: \( n^s = |E^s| \).
- \( n^s_{\text{new}} \): maximum number of AP to install. The network designer fixes the maximum number of new AP to be installed in the network.
- \( S^o \): subset of chosen sites for AP:
  \[ S^o = \{s \in S / \exists l \in L, (s, l) \in E^o\} \]
  \[ \{s \in S / \exists l \in L, w_a \in A\} \]
  with \( S^o \subset S \) and \( S^o \subset S^o \).
- \( c_o \): total cost for AP installation on the location \((s, l)\) that is, sum of costs of purchase, installation and connection to the network: \( c_o = c^w_s + c^s \).

When \( w_a \neq 0 \), we must define the parameters settings for the AP: frequency channel, emitted power and azimuth.

2. \( f_s \): frequency channel number used by the AP located on \((s, l)\): \( f_s \in F_s \).

3. \( P^s \): emitted power by the AP located on \((s, l)\):
   \[ P^s \in P_{w_a} = \{5,10,15,20\} \]

4. \( h_a \): azimuth of the AP located on \((s, l)\): \( h_a \in H_{w_a} \).

To summarise the model explained in this section, the AP parameters settings is characterised thanks to the parameter \((s, l, a, p, h, f)\) where: \((s, l)\) defines the location, \( a \) is the type of AP used, \( p \) is the emitted power, \( h \) is the azimuth or the horizontal orientation and \( f \) is the number of the frequency channel used. Then, the issue of the WLAN ACP/AFP process is the configuration of a set of AP for the whole building.

### 3.2 Case study of AP parameters setting

The following case study (Figure 2) is given for two different types of AP, one omnidirectional and one directive. Also, at each site, two sectors are defined, that is: \( A = \{1, 2\} \) and \( n^s = 2 \). The network uses the 802.11b/g standard, so \( f_s = 2.4\text{GHz} \), \( F_s = \{1,\ldots,13\} \) and \( n^s = 13 \).

- If \( a = 1 \), that corresponds to AP Cisco C1100
  - \( r_s \): circular pattern (omnidirectional antenna)
    \[ g_s = 2 \text{dBi}; H_s = \{0°\}; n^H_s = 1 \]
    \[ P_s = \{5, 10, 15, 20\}; n^P_s = 4 \]
    \[ b_s = 802.11\text{b/g}; c_s = 300 \text{€} \]
- If \( a = 2 \), that corresponds to AP Cisco C1000
  - \( r_s \): bidirectional pattern
    \[ g_s = 5 \text{dBi}; H_s = \{0°, 45°, 90°, 135°\}; n^H_s = 4 \]
    \[ P_s = \{5, 10, 15, 20\}; n^P_s = 4 \]
    \[ b_s = 802.11\text{b/g}; c_s = 400 \text{€} \]
The traffic model

The network traffic model defines the way of representing the network load demand; it also gives a framework to the expression of the desired QoS. In order to define the traffic demand, we use several service zones, which are represented by polygons covering parts of the building. Each of these zones is characterised by a number of users and a service type (mailing, videoconference, voIP, internet...) and consequently, by a throughput demand by user of this zone given in kilobits per second (kbps).

This traffic model is a continuous one. The polygons are rather vast zones capable of covering several rooms of a building; they can also overlap each other so the throughput demand per user is computed taking into account the overlapping areas of service zones. In the case study presented below, three service zones are defined and two of these are overlapping each other.

4 The traffic model

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4.1 Model description

The traffic model description is separated in three parts: the definition of the service zones themselves, then their discretisation in sets of pixels and finally, the bit rate computation for each pixel.

- \( Z \) set of service zones. The service zones are polygons drawn on each floor of the building (then \( n^v = |Z| \)).
- \( z \) the \( z \)th service zone, \( z \in \{1, \ldots, n^z\} \).
- \( n^z \) number of users inside the service zone \( z \).
- \( d^z \) bit rate in kbps desired by user for the service zone \( z \).
- \( d' \) total desired bit rate in kbps inside the service zone \( z \): \( d'_z = n^z \times d^z \).

Our model works on a discrete space, it is thus necessary to define a grid on the calculation area. The building zone is thus pixelised in the three dimensions of space.

- \( I + 1 \) number of pixels in the horizontal direction (\( O_x \)).
- \( J + 1 \) number of pixels in the vertical direction (\( O_y \)).
- \( K + 1 \) number of pixels in the height (\( O_z \)). It is the number of floors knowing that each floor is represented by a parallel plan with (\( O_{xy} \)).
- \( m_{i,j,k} \) the pixel \( ij \) where \( i \in I, j \in J \) and \( k \in K \).
- \( h_k \) height of the floor \( k \).
- \( \text{step} \) pixel step according to (\( O_x \)) and (\( O_y \)). The horizontal grid according to (\( O_{xy} \)) corresponding to the variables \( ij \) is orthonormal. The pixel step must
be equal to or higher than 1 m. The vertical pixeling according to \((OZ)\) corresponding to the variable \(k\) has a step of 1 per floor.

- \(n^*\) number of pixels:
  \[ n^* = (I + 1) \times (J + 1) \times (K + 1) \]

To integrate these service zones into our model, these service zones are represented by a set of points called Test Point. Each point corresponds to the centre of one pixel included inside the service zone.

- \(M\) set of pixels covered by service zone \(z\).
  \[ n^*_z = |M_z| \]
  \(\kappa\) number of users per pixel for the service zone \(z\): \(\kappa_z = n^*_z / n^*_M\).
  \(\tau\) rate, but by an integer value varying from \(-1\) to \(5\). The priority zones characterise the importance of certain zones of the building. These zones are defined and two of these are overlapping each other.

- \(\tau\) activity ratio of the TP \(t\). The users represented by the TP \(t\) are not always in communication, that is, emission or reception of signal. If one takes into account this activity ratio for a bit rate, one must consider that \(d^*_i\) rewrites itself in: \(d^*_i = d^*_i \times \tau\).

In the same way as for the service zones, we define priority zones. The priority zones characterise the importance of certain zones of the building. These zones are not characterised by a number of users or a desired bit rate, but by an integer value varying from \(-1\) to \(5\). The value \(5\) is the maximum priority value. The value \(0\) characterises a zone of null importance, like toilets. The negative value \(-1\) characterises a zone, which must not be covered, that is the received signal must be lower than the sensitive of the reception equipment; for instance, it may be zones outside the building.

- \(p\) priority value allocated to the TP \(t\).
  \[ p_t \in \{-1, 0, 2, 3, 4, 5\} \]

### 4.2 Case study of traffic modelling

In the case study presented here (Figure 3), three service zones are defined and two of these are overlapping each other.

### 5 The throughput model

In indoor wireless communications context, the propagation model defines how the signal is received inside the building. The throughput model transcribes these data into service level provided by the network, that is, bit rate offered to the clients. The principal parameters used in the bit rate calculation are the signal power and quality received by the client. The quality is defined by the signal to interference ratio where the noise is a part of interference (SINR Signal to Interference plus Noise Ratio). The association rule, which specifies the connection of one client to one AP, is also defined in the throughput model. It gives the number of clients associated per AP knowing that each AP shares its channels between all its associated clients. In the following case study we will check the throughput for two TPs from the computation of their received power and radio quality.

#### 5.1 Model description

In the following, we firstly describe the signal reception inside the building.

- \(p_{\text{th}}^i\) power of the received signal in the centre of the pixel \(m_{si}\) and coming from the location \((s, l)\). This power is expressed in dBm. Tests are made at 1 m 20 height above ground level.
- \(p_{\text{th}}^i\) power of the received signal by the TP \(t\) and coming from the location \((s, l)\): \(p_{\text{th}}^i = p_{\text{th}}^i\) if \(m_{si} = m_t\). Knowing the locations of the transmitting site \(s\) and receiving pixel \(m_t\), the decision variables \(w_{si}, p_{\text{th}}^i, h_{si}\), the frequency channel and the building topology, the propagation model, noticed \((\chi)\), determines the radio field received on this pixel:
  \[ p_{\text{th}}^i = \chi(s, m_{si}, w_{si}, p_{\text{th}}^i, h_{si}, f_{si}) \]

Radio field modelling is detailed in Walke (2002).

- \(p_i\) reception threshold. It is the minimum signal power a client must received to allow it to communicate.
- \(E_i\) set of open sectors for which the power received at the TP \(t\) allows it to communicate:
  \[ E_i = \{ (s, l) \in E^+ / p_{\text{th}}^i \geq p_i \} \text{ and } n_i^* = |E_i| \]

- \(p_i^*\) interference threshold. It is the minimum signal power a client can receive as interference.
- \(E_i^*\) set of open sectors for which the power received at the TP \(t\) is mobile sensitive, so can interfere the carrier on \(t\):
  \[ E_i^* = \{ (s, l) \in E^+ / p_{\text{th}}^i \geq p_i^* \} \text{ and } n_i^* = |E_i^*| \]

- \(p_i^{\text{best}}\) best received signal on the TP \(t\):
  \[ p_i^{\text{best}} = \max_{(s,l)\in E^+} (p_{\text{th}}^i) \]

Then, we define the radio quality computation which includes the SINR according to the frequency channels assignment on used AP.
Figure 3  Case study of traffic modelling

Then we illustrate the computation of $d^*_i$ in this example. That is the bit rate in kbps required by one test point $t$ where $t$ is overlapped by several service zones of different data rates. For more readability, we represent the test points by a point located at the centre of each pixel.

$$T = \bigcup_{z \in \mathcal{Z}} M_z = M_1 \cup M_2 \cup M_3 = \{ m_{3,1,0}; m_{3,2,0}; m_{4,1,0}; m_{4,2,0}; m_{4,3,0}; m_{5,0,0}; m_{5,1,0}; m_{5,2,0}; m_{5,3,0}; m_{6,0,0}; m_{6,1,0}; m_{6,2,0}; m_{7,0,0}; m_{7,1,0}; m_{8,0,0}; m_{8,1,0}; m_{8,2,0}; m_{9,0,0}; m_{9,1,0}; m_{9,2,0}; m_{9,3,0}; m_{10,0,0}; m_{10,1,0}; m_{10,2,0}; m_{10,3,0}; m_{11,0,0}; m_{11,1,0}; m_{11,2,0}; m_{11,3,0}; m_{12,0,0}; m_{12,1,0}; m_{12,2,0}; m_{12,3,0}; m_{13,0,0}; m_{13,1,0}; m_{13,2,0}; m_{13,3,0}; m_{14,0,0}; m_{14,1,0}; m_{14,2,0}; m_{14,3,0}; m_{15,0,0}; m_{15,1,0}; m_{15,2,0}; m_{15,3,0}; m_{16,0,0}; m_{16,1,0}; m_{16,2,0}; m_{16,3,0}; m_{17,0,0}; m_{17,1,0}; m_{17,2,0}; m_{17,3,0}; m_{18,0,0}; m_{18,1,0}; m_{18,2,0}; m_{18,3,0}; m_{19,0,0}; m_{19,1,0}; m_{19,2,0}; m_{20,0,0}; m_{20,1,0}; m_{21,0,0}\}.$$
Wireless LAN planning

- $p$ signal attenuation between channels. It is a function giving the signal attenuation (in dB) between two channels from their spectrum separation distance. The attenuation depends on several features such as WLAN standard and equipment.

- $\text{SINR}_d$, Signal to Interference-Noise Ratio at the TP $t$ for the AP located on $(s, l)$:

$$\text{SINR}_d = \frac{p_d}{p_b + \sum_{(j', s') \in E \setminus \{(s, l)\}} p_{j't}' \gamma (f_{d}, f_{T})}$$

Where $p_d$ is the thermal noise power. In this formula the notations are linear that is, the received powers are expressed in milliwatt. A division of two powers expressed in mW corresponds to their subtraction in dBm, then:

$$\text{SINR}_d = p_{d} - \left( p_{b} + \sum_{(j', s') \in E \setminus \{(s, l)\}} p_{j't}' \gamma (f_{d}, f_{T}) \right)$$

For a given client, there are two types of interfering signals: those coming from the AP not associated to the given client, they are downlink signals; those coming from all other clients, they are uplink signals. Usually in literature and also in practice, only the downlink signals coming from AP are taken into account to quantify interferences (Wong et al., 2003). In our approach as well, the uplink signal is not used for interference computation.

- $\text{SINR}_q$, the association rule links each TP to the AP providing the strongest signal. Thus the SINR main interest is the SINR of the best signal, given by:

$$\text{SINR}_q = \text{SINR}_{q,t}$$

$$\text{SINR}_q = \frac{p_q}{p_b + \sum_{(j', s') \in E \setminus \{(s, l)\}} p_{j't}' \gamma (f_{q}, f_{T})}$$

- $\text{SINR}$ minimal SINR threshold to communicate at the minimum nominal rate, that is the minimum service guaranteed by a technology regarding to the SINR. This threshold is for a given standard, so it is: $\text{SINR}^\text{a}$ for 802.11b, $\text{SINR}^\text{g}$ for 802.11g and $\text{SINR}^\text{a}$ for 802.11a.

The association rules are not fixed by the IEEE 802.11 standard and the manufacturers are free to implement their own rules. The main association uses by manufacturers linked the client to the AP corresponding to the best received signal with the minimal SINR. Our model adopts this rule. However other association rules may be proposed. From the association rule we now define the parameters linking the clients to the AP.

- $u_{s}$, decision variable to associate the TP $t$ to the AP located on $(s, l)$. $\forall t \in T, \forall (s,l) \in E^s$, $u_{s} = \begin{cases} 1 & \text{if } p_{d} = p_{s}^d \text{ and } p_{b} \geq p_{s} \text{ and } \text{SINR}_{d} \geq \text{SINR}_{q} \\ 0 & \text{else} \end{cases}$ $u_{s}$ is called the association variable.

If $\sum_{(s,l) \in E^s} u_{s} = 1$, the network covers the TP $t$.

If $\sum_{(s,l) \in E^s} u_{s} = 0$, the network does not cover the TP $t$.

- $(s, l)$ AP serving the TP $t$. We define the serving AP by: $s_{t} = s$ and $l = l$ if and only if $u_{s} = 1$; that is, the TP $t$ is associated to the AP located on $(s, l), s_{t} = 0$ and $l = 0$ if and only if the network does not cover the TP $t$.

Hence: $s_{t} = \sum_{(s,l) \in E^s} s \times u_{s}$ and $l_{t} = \sum_{(s,l) \in E^s} l \times u_{s}$. $T_{d}^s$ set of TPs served by the AP located on $(s, l)$: $T_{d}^s = \{ t \in T \mid u_{s} = 1 \}$. $T_{d}^s$ is the cell of the AP located on $(s, l)$.

$T_{00}^s$ set of TPs not covered by the network: $T_{00}^s = \{ t \in T \mid \sum_{(s,l) \in E^s} u_{s} = 0 \}$.

- $n_{t}^s$, number of users belonging to the cell $T_{d}^s$: $n_{t}^s = \sum_{s \in T_{d}^s} \lambda_{s}$. $T_{d}^s$ is the set of the AP $t$: $T_{d}^s = T_{d0}^s$. For an uncovered TP $t$: $T_{d}^s = T_{d0}^s$.

- $n_{t}^s$, number of users belonging to the cell $T_{d}^s$: $n_{t}^s = \sum_{s \in T_{d}^s} \lambda_{t,s}$. If the TP $t$ is not covered, $n_{t}^s$ gives the number of TPs not covered. Notice that: $n_{t}^s = n_{t}^s$ and $\forall t \in T, n_{t}^s \geq 1$.

From now, we define the maximum nominal bit rate according to the received power and to the radio quality on each TP.

- $q^d$ downlink maximum nominal bit rate on $t$ according to the received power and the standard with reference to $q^a$ for 802.11b, $q^g$ for 802.11g and $q^a$ for 802.11a.

The Table 1 gives an example of nominal bit rates for the standard 802.11b for downlink.

- $q^\text{SNIR}$ downlink maximum nominal bit rate on $t$ according to the SINR and the standard with reference to $q^\text{SNIR}$ for 802.11b, $q^\text{SNIR}$ for 802.11g and $q^\text{SNIR}$ for 802.11a.

The Table 1 gives an example of nominal bit rates for the standard 802.11b for downlink.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Coding</th>
<th>Modulation</th>
<th>Nominal bit rate (Mbit/s)</th>
<th>Maximal capacity</th>
<th>Maximal real bit rate (Mbit/s)</th>
<th>$q^d$ (dBm)</th>
<th>$q^\text{SNIR}$ (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>DSSS</td>
<td>BPSK</td>
<td>1</td>
<td>0.93</td>
<td>0.93</td>
<td>–94</td>
<td>4</td>
</tr>
<tr>
<td>802.11b</td>
<td>DSSS</td>
<td>QPSK</td>
<td>2</td>
<td>0.86</td>
<td>1.72</td>
<td>–91</td>
<td>7</td>
</tr>
<tr>
<td>802.11b</td>
<td>CCK(8bits)</td>
<td>QPSK</td>
<td>5.5</td>
<td>0.73</td>
<td>4</td>
<td>–88</td>
<td>11</td>
</tr>
<tr>
<td>802.11b</td>
<td>CCK(8bits)</td>
<td>QPSK</td>
<td>11</td>
<td>0.58</td>
<td>6</td>
<td>–85</td>
<td>16</td>
</tr>
</tbody>
</table>
\begin{itemize}
  \item $d^*_d$ downlink nominal bit rate (in Mbps) provided on $t$ by the AP located on $(s, l)$: $d^*_d = \min \left\{ q^p \left( p^*_d \right), q^{\text{SINR}} (\text{SINR}_d) \right\}$.
  \item $d^*_d$ as for the SINR, the bit rate of interest is the downlink nominal bit rate provided by the best serving AP, and: $d^*_d = \min \left\{ q^p \left( p^*_d \right), q^{\text{SINR}} (\text{SINR}_d) \right\}$.
\end{itemize}

Finally, we get all data to estimate the deviation between the required bit rate and the real bit rate provided by the network on each TP $t$.

\begin{itemize}
  \item $g$ function which gives the real bit rate provided by the serving AP in downlink according to $d^*_d$, the nominal bit rate and the number of users associated with this AP. This function also depends on other parameters as the number of users communicating with the AP at different nominal bit rate allowed by the standard. A thorough study of the MAC layer and the protocol CSMA/CA allow detailing this function, but this aspect is not tackled in this document. The 6th column of Table 1 is a set of value for $g$.
  \item $d^*_t$ real downlink bit rate (in kbps) provided by the network at the TP $t$: $d^*_t = g \left( d^*_d, n^t \right) / n^t$. If the TP $t$ is not covered, $d^*_t = 0$ because: $g(0, x) = 0$ and $d^*_d = 0$.
  \item $\Delta$ deviation between the downlink bit rate required at the TP $t$ and the bit rate provided by the network:
\end{itemize}

\[
\Delta = d^*_r - d^*_d
\]

Then:

\begin{itemize}
  \item If $\Delta \geq 0$, the TP request is satisfied.
  \item If $\Delta < 0$, the TP request is not satisfied.
\end{itemize}

\section{Case study of throughput modelling}

In the case study presented below (Figure 4), we consider two TPs, numbered 2 and 15 for the throughput computation. For both points will we search the best serving AP, then we will compute the SINR level on the best server and finally we calculate the throughput and the deviation from the expected bit rate.

\section{Problem to optimise}

The model introduced in the previous sections includes all parameters dealing with calculations; it is free of specific optimisation problem. Now we define this optimisation problem to solve. For any candidate company in WLAN deployment the main objective is to minimise the financial cost under some constraints on service quality and maximal cost installation threshold. The financial cost we consider as objective is not only the cost of the network deployment (sum of AP and site installation costs) but also the cost of unsatisfied demands given by $\Delta$. This term is directly representative of the QoS got on the network that is the correspondence between the required throughput and the real throughput for all TPs on the building according to their priority.

The last problem there is to find the right economical cost, in Euro, of 1 kbps loss on throughput. It is quite easy when considering one kind of service and one kind of access profile as we did, but in real world, one must create a table of economical costs of throughput leisure for all these different cases and replace the unique value by a set a values for each services on each TP.

\subsection{Model description}

The optimisation problem is thus to determine the decision variables $(w_s, p_s, h_s, f_s)$, those are site, sector, antenna pattern, emitted-power, azimuth and frequency channel, in order to minimise the following function:

\[
\sum_{r \in \mathbb{E}} c_s^r + \sum_{(s,l) \in \mathbb{E} \times \mathbb{I}} c^s_{w_s} + \beta \cdot \sum_{n \in \mathbb{E}} \max(0, -p_n \Delta_n)
\]

Where, $p_n$ is the priority assigned to the TP $t$ and $\beta$ is the economical cost, in Euro, of 1 kbps loss on throughput.

In this function, the 1st term is the sites installation cost, the 2nd is the purchase and installation costs of AP, and the third term defines the cost of unsatisfied demand. All components are in Euro. So the WLAN deployment challenge is completely traduced as an economical challenge for the network designer, which is perfectly understandable for the designer customer.

The optimisation must be done under the following constraints:

\begin{enumerate}
  \item [(C1)] $\forall t \in \mathbb{T}, \sum_{(s,l) \in \mathbb{E}} a_{s,l} = 1$ \label{C1}
  \item [(C2)] $n^s \leq n^{\text{max}}$ \label{C2}
  \item [(C3)] $\forall (s,l) \in E \setminus E'$, $w_{s,l} \in A \cup \{0\}$ \label{C3}
  \item [(C4)] $\forall (s,l) \in E' \setminus E'$, $f_s \in F_s$, $p_s \in P_{w_s}$, $h_s \in H_{w_s}$ \label{C4}
\end{enumerate}

where:

\begin{itemize}
  \item (C1) indicates that the network covers all TPs with a minimum guaranteed service proposed by the customer.
  \item (C2) indicates that the maximum number of newly installed AP does not exceed $n^{\text{max}}$ given by the customer.
  \item (C3) is the domain of definition of the decision variables $w_{s,l}$ for free locations that is the set of locations: $E \setminus E'$.
  \item (C4) is the domain of definition of the decision variables $f_s, p_s, h_s$ for the new AP located on $E \setminus E'$.
\end{itemize}
Figure 4  Case study of throughput modelling

Received powers map from sector (s,t) = (2,2)

Power of the received signal at test point 2 (pixel m_{2,2,2}):
\[ p_{2,2,2}^r = -77.5 \text{ dBm} \]
\[ p_{2,2,2}^t = -102.6 \text{ dBm} \]

Power of the received signal at test point 15 (pixel m_{4,1,5}):
\[ p_{4,1,5}^r = -65.5 \text{ dBm} \]
\[ p_{4,1,5}^t = -93.0 \text{ dBm} \]

Received powers map from sector (s,t) = (4,1)

Then we use: \( p^r = -94 \text{ dBm} \) for Cisco Aironet 350 series client adapters and \( p^t = -100 \text{ dBm} \) as the thermal noise power.

Let consider \( q^p \) and \( q^{SINR} \) from the table 1 (802.11b standard) and \( g(11\text{Mbps}) = 6 \text{ Mbps} \). As well we assign the following channels: \( f_2 = 3 \) and \( f_3 = 1 \) with \( \gamma(f_2, f_3) = -5.7 \text{ dB} \) (this value is arbitrary defined).

For the test point 2:
\[ E_{12}^r = \{ (2,2) ; n_2^r = 1 \} \]
\[ E_{12}^t = \{ (2,2) ; n_2^t = 1 \} \]
\[ p_{2,2,2}^r = -77.5 \text{ dBM} \]
\[ u_{2,2,2} = 1 ; l_{2} = 2 \]
\[ \text{SINR}_{2} = 77.5 - (-102.6 - 5.7) = 30.8 \text{ dB} \]
\[ d_{2}^r = \min\{q^p(p_{2,2,2}^r), q^{SINR}(\text{SINR}_{2})\} = 11 \text{ Mbps} \]
\[ d_{2}^t = \frac{g(d_{2}^r, n_{2}^t)}{n_{2}} = \frac{6}{29.3} = 205 \text{ kbps} \]
\[ \Delta_2 = d_{2}^r - d_{2}^t = 175 \text{ kbps} \]
(recall: \( d_{2}^t = 30 \text{ kbps} \))

The test point 2 is satisfied.

For the test point 15:
\[ E_{15}^r = \{ (2,2) ; (4,1) ; n_5^r = 2 \} \]
\[ E_{15}^t = \{ (2,2) ; (4,1) ; n_5^t = 2 \} \]
\[ p_{15}^r = -65.5 \text{ dBm} \]
\[ u_{2,1,5} = 1 ; l_{1} = 2 \]
\[ \text{SINR}_{15} = 65.5 - (-93.0 - 5.7) = 33.2 \text{ dB} \]
\[ d_{15}^r = \min\{q^p(p_{15}^r), q^{SINR}(\text{SINR}_{15})\} = 11 \text{ Mbps} \]
\[ d_{15}^t = \frac{g(d_{15}^r, n_{15}^t)}{n_{15}} = \frac{6}{50.7} = 118 \text{ kbps} \]
\[ \Delta_{15} = d_{15}^r - d_{15}^t = 68 \text{ kbps} \]
(recall: \( d_{15}^t = 50 \text{ kbps} \))

The test point 15 is satisfied.

On the figure below, we assign the test point to both AP. The colour codes of test points are those of the service zone including them. The green line is the separation of test points association: on its left, test points are associated to AP (2,2), and to AP (4,1) on the other side.

Clients associated to AP located on (2,2).
\[ T_{2,2}^c = T_{2}^c = T_{15}^c = \{ 1, 2, 3, \ldots, 26, 27 \} \]
\[ n_{2,2}^c = n_2^c = n_{15}^c = \sum_{i \in T_{2,2}} k_i^c = 29.3 \text{ users} \]

Clients associated to AP located on (4,1).
\[ T_{4,1}^c = \{ 28, 29, 30, \ldots, 30, 40 \} \]
\[ n_{4,1}^c = \sum_{i \in T_{4,1}} k_i^c = 50.7 \text{ users} \]
6.2 Case study of the model

In reference to our last case study given in V, the WLAN configuration with 2 AP (set {(2, 2, 20, 0, 3); (4, 1, 1, 20, 0, 1)}) costs 650 €. It corresponds to the first two terms of the function to optimise. For this configuration, all clients are satisfied; there is no additional cost linked to unsatisfied demand.

6.3 Problem reduction to a partitioning problem

When the most important decision variables are the location choice, for instance for the deployment of small size networks, the problem may be reduced to a partitioning problem. While being interested neither in the AP parameter settings, nor in the maximum number of AP to be placed, the problem may be hugely simplified. The problem is then to determine the set of AP locations to open and is reduced to a partitioning problem.

In this case, the position \( l \) makes no sense; \( w_s = y \) could thus take only 2 values: 0 when the site \( s \) is closed and 1 when the site \( s \) is open.

This reduced problem is then to determine the decision binary variable \( w_s \) in order to minimise the function below:

\[
\sum_{s \in S} c_s^T \sum_{s \in S} c_s^T y_s
\]

Under the constraints:

\[
(C1) \quad \forall t \in T, \quad \sum_{l \in S} u_{st} = 1 \Leftrightarrow \forall t \in T, \quad \sum_{s \in S} x_{st} y_s = 1,
\]

where \( u_{st} = x_{st} \)

\[
(C2) \quad \forall s \in S, \quad x_s = 0 \text{ or } 1
\]

where the vector \((c_s^T)_{s \in S}\) is known and the matrices \((x_s)_{s \in S} = (u_{st})_{t \in T, s \in S}\) are known.

On the opposite, another problem reduction is to consider the locations already selected. The problem then becomes a resources distribution problem: there is nothing left other than defining the parameters of the AP.

7 Conclusions and future work

A well-defined single optimisation problem did not exist to deal with all the various cases met in WLAN planning but actually there are as many problems as formulations and combinations of technical and economical criteria.

In this paper, we presented a model that defines all major parameters met in the WLAN planning problems found in literature. This model offers a complete and formal structure for automatic WLAN planning including ACP and AFP features as a unique process where all parameters are evaluate all together and not in sequence from ACP to AFP as often. It however leaves the place to particular modules and evolutions such as specific wave propagation model to compute the received power, network association rules to computer transmitter loads and real data rate estimation from specific MAC/PHY layers simulator. The great advantage of this new model is that our computation of network evaluation is done on a single way from the received power to the real throughput, through the signal-to-interference ratio including all available frequency channels of the WLAN system and multiple interference computation.

Another particular point we proposed is the combination of economical criteria in Euro inside a unique objective function. Sites installation costs, purchase and installation cost of AP and throughput satisfaction criteria are linked together in the same unit. To reach this model the throughput loss in kbps is associated to a given economical cost given in Euro. Then the unique economical objective function is able to deal with all technical criteria linked to throughput modelling per client such as coverage, interference and network capacity. This objective function definition is directly linked to the ACP/AFP unified approach, as we cannot define such location cost and throughput cost criteria inside one objective function without dealing with both problems as a whole.

Knowing the difficulty to rapidly understand the formal model, our work proposed also a didactical explanation through a short example illustrating all data, variables and functions used. The model we defined is then illustrated with several case studies to allow the reader to perfectly sense the component of the planning process. This work is also useful to get a better understanding of WLAN network features.

The further step of this work is to conceive some optimisation algorithms to deal with the problem. We are currently working on it based on meta heuristic approaches. Our last objective is not only to model and to solve the problem but also we will bring to the community several datasets and several results to allow optimisation teams to work on that problem and compare different kind of algorithms, which is a long and hard task to come.

References


Wireless LAN planning


Note

France Telecom grants this work.