Indoor wLAN Planning with a QoS constraint based on a Markovian Performance Evaluation Model

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***Abstract*— This paper proposes an automatic base station planning approach. This approach does not only try to assess usual objectives such as radio coverage, but further implements a Quality of Service (QoS) constraint. This criterion is here defined as the mean available bandwidth per user. Its computation takes the medium access control (MAC) layer behavior, the multiple bit rates of IEEE802.11b and the coverage area of each access point (AP) into account. A Markov chain is used to evaluate the available bandwidth of each cell independently. This is sensible because a non-overlapping criterion between cells is used during the planning phase to avoid interference between adjacent cells. The planning process estimates an optimal number of APs and their placement minimizing an aggregate criterion using a Tabu meta-heuristic. The AP's coverage is estimated with a powerful multi-resolution radio propagation simulator previously described. This paper presents results for a QoS oriented planning process providing a predefined minimum per-user throughput. The example provided herein applies for 100 users distributed over a 12600 m^2 building floor.**

***Index Terms*— wireless network planning, QoS estimation, 802.11**

I. Introduction

Although a lot of wireless LAN (wLAN) APs' placement are successfully realized every day by radio engineers, only few planning tools are available. The exponential growth of such networks lead to the need for developing automatic planning techniques based on radio-frequency propagation predictions. In the last decade, indoor wLAN planning mainly focused on coverage and cell-overlapping optimization criteria. Recent works are now devoted to more sophisticated criteria aiming to ensure a level of quality of service (QoS) for connected users. The QoS may be considered from many different points of view. Either the bandwidth per user or the network capacity seem to be relevant. The forthcoming questions are twofold. The former concerns the formulation of such a QoS criterion in a wLAN planning problem and the later the evaluation of such a criterion. In ([1], [2], [3]), it is assumed that the available aggregate bandwidth of an access point is fixed, albeit stochastic performance evaluation of 802.11 shown different results. Indeed in ([4], [5]), the available bandwidth of an AP was shown decreasing with an increasing number of connected users, because of two main reasons. Firstly, larger is the number of users, lower is the efficiency of the CSMA/CA protocol and higher is the collision rate. Secondly, the way the throughput is shared between users strongly depends on the number of users working at different data rates as described in section III. Therefore, an accurate estimation of the QoS of IEEE 802.11 networks relies on a fine performance evaluation of the 802.11 MAC layer. Previous performance evaluation works assumed an ideal channel propagation and no interferences.

In this paper, we propose to define a new QoS criterion exploiting the results of a realistic stochastic model of 802.11. This QoS criterion is then used for a wLAN planning algorithm. The stochastic performance evaluation model used computes the available aggregate throughput of an access point for each 802.11b data rate. This throughput is obtained by solving a Markov chain describing the IEEE 802.11b MAC protocol. The number of users served by each AP and the data rate associated with are estimated with the help of wave propagation simulations provided by a home-made radio propagation simulator ([6], [7]). The mean throughput per user and per class of service is obtained by dividing the aggregate throughput of an AP by the number of users it covers at a given data rate. The QoS planning criterion is directly based on this mean data rate. It is worth noting that our QoS criterion doesn't take inter-cell interferences into account. For this reason, an additive non-overlapping criterion is introduced to reduce both the overall interference level and the complexity of the frequency assignment problem (FAP). Both QoS and non-overlapping criteria are optimized concurrently to get a trade-off solution between throughput efficiency and interference avoidance.

The FAP problem is not studied herein but simple heuristics are efficient enough (see [8] for instance) for 802.11b networks. Assessing an optimal network infrastructure is a difficult task because changing an AP location modifies the best server coverage map and thereby the distribution of users covered by each AP. That is why the aggregate throughput of each AP has to be evaluated for each solution. This work uses a Tabu metaheuristic therefore.

The paper is organized as follow. Section II describes related work by focusing on both wLAN planning and performance evaluation results. Section III presents on our global model. The planning objectives and some details on the QoS criterion based on a Markov chain are given. Section IV provides implementation details, focusing on propagation simulations, combinatorial optimization formulation and Tabu search algorithm. Section V shows some simulation results obtained with a real environment. Finally, concluding remarks and perspectives are developed in section VI.

II. Related Work

A. WLAN planning background

First planning challenges dealt with accurately evaluating AP's coverage in the complex indoor environment to ensure basic network access ([9], [10]). Then, to withdraw multiple cells' interference, the problem of distributing the sparse frequency bandwidth allocated to indoor wLAN channels has been issued. Frequency allocation problems were studied and constraints on the Signal to Interference Ratio (SIR) [11] and cells' overlapping [1] were introduced in the AP planning process.

Practical use of wLAN showed the strong dependence between the network performance and users' demand. Therefore, in the last two years, optimization models distributing the AP's available bandwidth between users have been proposed. In ([1], [2], [3]), a set of users demanding for a given amount of traffic and a set of candidate APs with a fixed available bandwidth are defined. When an AP can not provide enough capacity to the users it covers, a traffic constraint is violated ([1], [2]). [1] proposed an integer linear program handling traffic as a constraint on each access point capacity but also as a global planning objective that minimizes the maximum of channel utilization of the access points covering the area.

[3] proposed a quadratic program where the impact of interference on network capacity is taken into account. The network capacity is measured as the ratio between a theoretical fixed capacity and the number of users that belong to interference range of each network AP. They consider here that the capacity shortfall of the network is mainly due to inter-cell interference.

Thus, planning processes dealing with optimizing QoS consider that the AP's bandwidth is always fixed although 802.11b performance evaluation results show that this assumption is not realistic, as it is described thereafter.

B. Performance evaluation

A lot of works ([4], [12], [13]) deals with performance evaluation of 802.11 Medium Access Control (MAC) protocol. These papers propose analytical models evaluating the throughput, delay or the influence of slow stations on the global wLAN performance. Such models take basic access or RTS/CTS (Request To Send / Clear To Send) mechanisms into account but they assume an ideal radio medium. Indeed, neither interference nor bit error rate are taken into account. In fact, these articles concentrate on the presence of collisions in 802.11. A collision occurs when several stations transmit packets on the medium at the same time. These simultaneous transmissions result in packet transmission errors, leading to a retransmission process. Hence the medium is occupied for useless activities, degrading overall network performance.

Nevertheless, three phenomena influence the radio transmission: *(i)* collisions, *(ii)* quality of the radio link and *(iii)* interference. Collision effects are well-known. Quality of the radio link depends not only on the basic electronic noise level but also on the distribution of the stations and the topology of the environment (wall's position, thickness, etc ...). Besides, the presence of multiple APs also introduce interference, decreasing transmission quality.

In this paper, the wLAN planning algorithm exploits a network performance evaluation model derived from a Markov chain modeling a realistic wLAN environment: collisions and radio link quality are both taken into account.

III. Problem Formulation

A. The Planning Objectives

A wLAN planning task is firstly based on a mathematical description of several objectives. A first fundamental objective is to ensure a radio coverage everywhere offering to the mobile user a full connection. A complementary objective concerns the access network efficiency, which relies mainly on the interference level between cells. Additionally, a more pertinent objective should be user-oriented. A user-oriented objective allows to control the access network deployment under usage constraints.

To fulfill simultaneously several constraints, the wLAN planning problem may be formulated as a sum of complementary constraints. The planning process aiming to minimize a single aggregate evaluation function f is thus defined as:

$$f = \alpha_1 \ . \ f_{cov} + \alpha_2 \ . \ f_I + \alpha_3 \ . \ f_{QoS} \qquad (1)$$

where f_{cov}, f_I and f_{QoS} stand respectively for the coverage, non-interfering and QoS criteria. The coverage criterion is described in section III-A.1; the non-interfering one in section III-A.2 and the QoS one in section III-A.3.

The problem is dealt with as a combinatorial optimization problem. For this purpose a set of M candidates is defined as the set of possible AP locations over the environment. The way these locations are chosen is described in section IV. The simplest approach considers omnidirectional and constant power access points. In this case, the combinatory space is represented by an ON/OFF state of each possible candidate. The management of the transmitting power and directional antennas can be introduced by increasing the number of states of each variable, including an orientation and a power level. This paper focuses on the simplest model, considering constant power and omnidirectional transmitters.

1) Coverage Criterion: Let assumed that the coverage map of each candidate is computed for a representative set of test receiver points $b_{(i,j)}$. The mean received signal power from AP candidate number k on $b_{(i,j)}$ is referred thereafter as $F^k_{(i,j)}$. The coverage criterion is computed as a function of the power of the strongest signal in each point according to:

$$f_{cov} = 1/N_R \ . \sqrt{\sum_{b_{(i,j)} \in R} Q(F^{BS}(i,j))^2} \qquad (2)$$

where $F^{BS}(i,j)$ and N_R stand respectively for the received signal power of the best server AP and for the number of test points $b_{(i,j)}$. The penalty function $Q(F)$ can take several forms. It should be defined as a decreasing function having lower and upper bounds, allowing to drive carefully the quality of the network. Choosing a lower bound equals to zero allows to have a null value of the criterion if the hardest constraint is fulfilled. In the opposite the upper bound allows to avoid the strong effect of small areas having a lack of signal. Our penalty function $Q(F)$ is thus given by:

$$Q(F) = \begin{cases} 0, & \text{for } F \geq S_{11} \quad (3) \\ F - S_1, & \text{for } S_1 \leq F \leq S_{11} \quad (4) \\ S_{11} - S_1, & \text{for } F \leq S_1 \quad (5) \end{cases}$$

S_1 and S_{11} stand for the minimum signal powers that ensure respectively a 1 Mbits/s and 11 Mbits/s transmission rates. Simulations are made with $S_1 = -94$ dBm and $S_{11} = -82$ dBm. These values come from the 802.11b Lucent Orinoco© PCMCIA receiver card specifications. Note however that this approach can be easily adapted to either $802.11g$ or $802.11a$ equipments by setting the thresholds accordingly.

2) Non-interfering Criterion: In a CSMA/CA based network the radio medium is shared between all sensing nodes. However, two neighbor cells having different but overlapping frequency channels cannot share efficiently the medium because the carrier sense mechanism doesn't work. With 802.11b equipments, the number of non overlapping channels is very poor (about 3 or 4), and interference minimization becomes untractable when increasing the number of cells neighboring each other. The more robust approach to minimize interferences would be to include the frequency assignment problem (FAP) into the optimization process. In such an approach however, the computational time associated with the evaluation of each configuration would drastically increase because for each APs configuration, a frequency assignment should be proposed. Therefore, either a FAP algorithm should runs at each step, or the channel can be added as a variable into the combinatorial optimization problem [14], [15]. Because both approaches lead to a wide increase of the computational time, we rather propose a two-step approach, solving the FAP after the planning task. But our approach is made more robust than a usual two-step approach by introducing a non-interfering criterion. This criterion acts by maintaining low the number of adjacent cells, making easier the *a posteriori* FAP.

At a test point $b_{(i,j)}$, received signal powers $F^k_{(i,j)}$, $k \in [1, N]$, exceeding the noise level S_N, are ordered from the strongest to the weakest:

$$F^{BS}_{(i,j)} \geq F^1_{(i,j)} \geq \cdots \geq F^l_{(i,j)} \geq F^{l+1}_{(i,j)} \geq \cdots \geq S_N \qquad (6)$$

To manage the number of adjacent cells, enabling handover between h APs while limiting interferences with others, the following criterion divides received signals into three subsets : the best server signal ($l = 1$), adjacent signals ($1 < l \leq h$) and interfering signals ($l > h$). Then the criterion try to keep low the highest interfering signal, i.e. for $l = h + 1$:

$$f_I = 1/N_R \, . \sqrt{\sum_{b_{(i,j)} \in R} \max(S_N - F^{h+1}_{(i,j)}, 0)^2} \qquad (7)$$

This formulation has been adapted from [16] initially proposed in the framework of cellular planning. In our simulations the noise level is fixed to $S_N = -98$ dBm and the number of adjacent signals is set to $h = 1$. h is chosen very small because of the small number of independent channels. Note that h represents the number of adjacent cells seen from a specific receiver point, but absolutely not the number of neighboring cells. To manage the neighboring of each cell directly, a cell-based criterion should be used. Also it could appear more efficient, we disregard such an approach because of the higher computational requirement.

3) QoS Criterion: In this paper, a QoS-based criterion implementing a *per-user throughput* constraint is proposed. Previous works introducing such a constraint considered a unique data rate for all nodes and a perfect bandwidth sharing between nodes, keeping constant the total bandwidth [1], [2], [3]. In a $802.11b$ network however several users share the bandwidth at 4 different data rates 1, 2, 5.5 or $11 Mbits/s$ and even more with $802.11g$ networks. Our contribution aims to introduce a more realistic sharing model.

This criterion aims to maximize the raw throughput of each cell isolated from each other, i.e without interference. In our approach, co-channel interferences are maintained low firstly by the non-interfering criterion defined above and secondly by a later optimal channel assignment. This criterion provides an upper-bound of the per-user throughput, which may be degraded by interferences. In the minimization process a trade-off between QoS and interferences criteria will be obtained. All the users are divided into class of service groups, each group having its own aggregate throughput $D_1, D_2, D_{5.5}, D_{11}$. It is also assumed that the aggregate throughput of each service area $D_a, a \in \{1, 2, 5.5, 11\}$ is equitably distributed between the associated N_a users. The throughput $d_{(i,j)}$ associated with a user located in $b_{(i,j)}$ thus depends on the service area it belongs to, and is estimated by:

$$d_{(i,j)} = D_a/N_a \qquad (8)$$

The key point of this approach holds in the estimation of the aggregate throughput for each group. This problem is dealt with in III-B.

Finally, the throughput per user is constrained to be higher than a limit $D^*_{(i,j)}$ for each test point $b_{(i,j)}$, by the use of the following QoS criterion:

$$f_{QoS} = 1/N_R \, . \sqrt{\sum_{b_{(i,j)} \in R} \max(D^*_{(i,j)(dB)} - d_{(i,j)(dB)}, 0)^2} \qquad (9)$$

where the throughput values are computed in dB ($d_{dB} = 10.\log(d_{bits})$), so that the order of magnitude of the QoS criterion is comparable to the other ones.

B. Markovian performance evaluation model

As described above the QoS criterion requires a model of bandwidth sharing between nodes. We use an improved Markov Chain model (based on [4]) to evaluate a wLAN network throughput of a group of mobile users associated with the same AP.

All details are given in [17] but, due to a lack of place, only the key points are herein discussed.

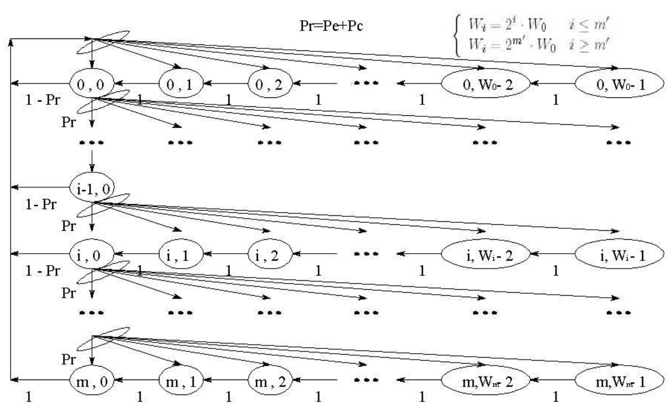

Fig. 1. Markov chain of 802.11 wLAN radio environment

In the chain presented in figure (1), the two-dimensional process {s(t),b(t)} is a discrete-time Markov chain where $s(t)$ is a stochastic process representing the backoff stage of a given wireless station at slot time t and $b(t)$ is a stochastic process representing the backoff time counter for the station. P_c is the probability of collision with other stations and P_e is a radio factor introduced to model the packet error probability due to interferences. It is important to note that P_e is independent from the CSMA/CA mechanism but depends only on the radio environment, the received power, the transmission data rate and the presence of obstacles. Hence, $P_r = P_e + P_c$ models the retransmission probability due to either collisions or radio transmission error. Using this Markov chain, we can derive the probability that one station transmits at data rate 1, 2, 5.5 or 11 Mbit/s, the channel occupation efficiency for each type of nodes and the duration for which the channel is occupied by either successful or unsuccessful transmissions leading to retransmission.

It is worth noting that the channel occupation of a data flow depends on its data rate. With a same medium access probability (guarantied by 802.11 protocol), a station transmitting at 1Mbps occupies the radio medium much longer than a station transmitting the same packet at 11Mbps. Hence, in a wLAN cell where stations working at different data rates, each group of stations working at one data rate should be considered separately from another group. In our model, the radio coverage map representing the received signal power in the building floor is divided into four areas $A_1, A_2, A_{5.5}, A_{11}$ standing for the areas where stations are working at the same data rate. Changing from transmission rate r_i to rate r_j occurs when the signal to noise ratio passes some thresholds fixed according to the IEEE802.11b standard. The Markovian model provides the average medium occupation time for each area. Then, a global average throughput can be easily deduced (see resolution method in [17]).

The efficiency of this model is assessed by an experimental evaluation. The estimated throughput of different number of stations in the network, predicted by our Markov chain mode, are plotted in figure (2) in order to compared to real experimental values obtained in saturation scenarios with one AP. The measurements are collected by sniffing the physical medium. This method provides real-time results where synchronization problems between sender and receiver don't occur. Our test-bed is made of an ALLIED© AP linked to a sink PC and 6 mobile stations equipped with Lucent Orinoco© PCMCIA receiver cards. RTS/CTS was deactivated as well as WEP encryption as they drastically reduce MAC performance. All the stations tried to send as fast as possible to the sink PC via the AP. We used the *MGEN* tool [18] to generate a tuned UDP/IP traffic and to log the traffic received on the sink PC for analysis. We used the *Ethereal* sniffer to capture all the packets present on its wireless interface. We placed the sniffer wLAN card very close to the AP antenna so that we can consider that the sniffer has captured all the traffic received by the AP.

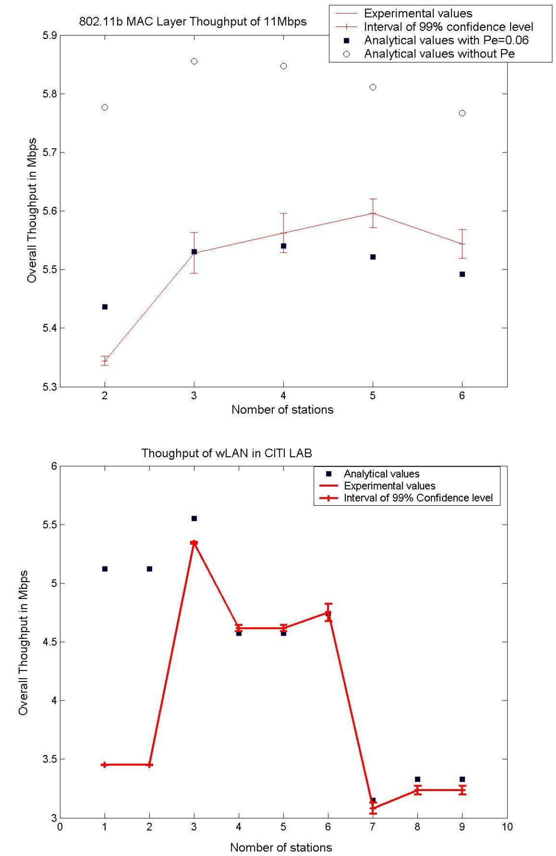

Fig. 2. Analytical and experimental results for throughput evaluation

For each experimental scenario performed, the average throughput has been computed with 99% confidence interval on the samples collected within a time interval. According to Fig. 2 the experimental curve fits well the analytical one if parameter p_e is adjusted. For example, in the scenario where all the stations transmitted at 11Mbps, making p_e equal to 0.06, the analytical curve is really close to the experimental one. We also observe that the lower the transmission rate is, the smaller the p_e is. Intuitively, this phenomenon can be explained by the fact that the reception power quality requested is related to the transmission rate. When a station works at a lower rate, the reception power requested for a good transmission is lower too, which makes the probability of the transmission error smaller. In each figure, the appearance of the analytical curve is almost the same as the experimental curve, which proves that our analytical model is close to what happened on the medium during experimentation.

IV. Implementation

A. The Propagation Simulation

The performance evaluation model and the planning process both require a propagation simulation tool. In this work, a home-made simulator, WILDE, is exploited [7]. This simulator implements the Multi-Resolution Fourier Domain ParFlow (MR-FDPF) model [6]. This propagation prediction model is based on a finite difference frequency domain modeling. This kind of approach is known to be very realistic but in turn computational-load consuming. The originality of our approach described in [6] was to gather all the computational load into a pre-processing phase, exploiting a multi-resolution formalism. This pre-processing phase is not dependent on the APs' characteristics. Thus, in the propagation phase, the computational load dedicated to the calculus of the coverage of an AP remains low (less than 1s. for environments about $100m \times 100m$), being comparable to the time needed with a standard multi-wall model (MWM). But while these standard approaches compute the received power from the main path only, our approach exploits all paths, including all reflected and diffracted rays. The first advantage of the MR-FDPF model is thus that multiple reflection and diffraction effects of radio waves are fully taken into account. The second one is that the multi-resolution concept allows to compute the mean power over homogeneous blocks instead of computing the mean power in each pixel, reducing further the coverage computational time. In this approach, the environment is divided into homogeneous regions, the blocks, and the received power $F^k_{(i,j)}$ in (i,j) from AP number k is estimated over each block $B(i,j)$ defined by its left hand corner $p = (x,y)$ and dimension $s = (l,h)$ in pixels. This model has been experimentally assessed in Indoor environment, leading to a mean square error of about $5dB$ [7].

B. The Tabu Optimization Algorithm

The planning problem is set using a discrete formulation. A solution is given by a subset of $N, N \in [1, \infty[$ antennas among M candidate APs' locations. Each solution is evaluated using the cost function given by equation (1). Finding the best solution is a hard optimization problem because :

- the size of the solution space grows exponentially: $\text{Card}(S) = \sum_{n=1}^{\infty} \binom{N}{n}$,
- the aggregate function is non-convex,
- a single solution evaluation lasts several milliseconds.

This calls for the use of a meta-heuristic and therefore a tabu approach [19] has been implemented. Tabu algorithms perform successive local search within the neighborhood $V(S)$ of the current solution S. The best solution in this neighborhood is chosen as the new current solution. To avoid local convergence and cycling problems, a memory called the Tabu list stores the choices made in the last T iterations. If the best solution found in $V(S)$ belongs to the tabu list, the move is forbidden and the second best solution is selected. This algorithm has been implemented with the following features:

a) A solution: S is defined as a vector of M binary items $S = (s_1, \ldots, s_i, \ldots, s_{M)}$ where $s_i = 1$ if the i^{th} candidate AP belongs to the solution.

b) A neighbor solution: is obtained either by moving one candidate AP from position i to j, or by adding an AP or by removing a selected AP. The cardinal of $V(S)$ is equals to $N(M-N) + M$.

c) The Tabu list: stores the last moves carried out, which, for this reason, are forbidden. It can be referred to as the short-term memory that enables the algorithm to escape from local minima and withdraw cycling round during the search process. In this implementation, our tabu list stores the items s_i. A solution of the neighborhood which has the item s_i assigned one of its transmitter is Tabu and can not be selected for the next search iteration. After a move from s_1 to s_2, item s_1 is stored in the Tabu list.

This short term memory has a length T that can be fixed or chosen randomly at each iteration. At each iteration the length T of the tabu list is randomly chosen between two user-defined parameters T_{min} and T_{max}. When T is reduced, the oldest moves, which exceed the new length of the list, become feasible. The initial value of T is chosen in the same way.

d) Termination criteria:: The algorithm stops when one of the following termination criteria is satisfied:

- the number of iterations has reached the maximum number of iterations NI_{max},
- the number of successive iterations without improvement of the cost function has reached a specified number NWI_{max},
- the cost function returned value is equal to zero.

e) The parameter values : were tuned empirically after several tests as it is recommended in [20]. We fix $T_{min} = M/5$ and $T_{max} = M/2$ with M the number of transmitters. In the same way, we fix $NI_{max} = 1000$ and $NWI_{max} = 200$.

V. Results

A. Test environment

The test environment shown in figure (3) is the ground floor of a 12600 m^2 building. The M candidate positions ($M = 257$) have been chosen at the center of some selected blocks associated with the multi-resolution structure of the WILDE propagation simulator. A block in the pyramid is selected if and only if it is made of air and if its surface S is bounded : $1m^2 < S < 10m^2$. Larger homogeneous blocks are further divided and smaller blocks are disregarded. Because a selected block is only made of air, it seems sensible to assume that the radio coverage of a candidate AP placed in the center of this block is representative of the coverage of others APs in the same block. The power of APs is assumed constant delivering 15 dBm and antennas are assumed omnidirectional. There is only one interferer allowed ($h = 1$). Since the QoS criterion needs a repartition of simultaneous users, 100 users are assumed homogeneously distributed. From this distribution, the number of users associated with each AP, and their corresponding class of service is achievable. The

TABLE I

PLANNING RESULTS: EVALUATION FUNCTIONS AND SEARCH TIME.

Test	n	f_{cov}	f_I	f_{QoS}	T	N_s
1	5	0.15	0.0	1.53	440s ($\simeq$ 7mn40s)	54081
2	6	0.10	3.08	0.02	400s ($\simeq$ 6mn40s)	11487
3	11	0.0	12.03	0.07	620s ($\simeq$ 10mn20s)	47828

TABLE II

PLANNING RESULTS: PERFORMANCE OF THE SOLUTIONS

Test	P_{cov}	P_O	P_I	P_{QoS}	d_m
1	100 %	100 %	100 %	23 %	256 Kbits/s
2	99.5 %	70 %	100 %	61 %	300 Kbits/s
3	100 %	18 %	100 %	89 %	597 Kbits/s

probability of having a user in each pixel is uniform and is computed as the ratio between the number of users and the number of pixels.

The algorithm starts with an initial solution of $n = 4$ APs chosen randomly over the full search space. An interval $I = [40, 140]$ for the tabu list size has been chosen empirically according to [20].

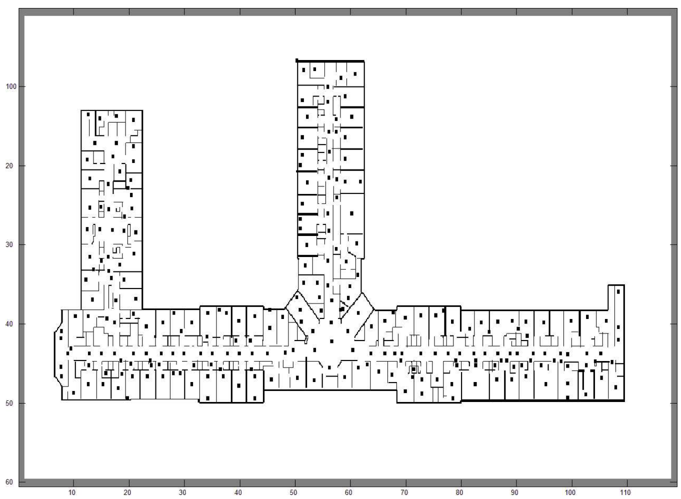

Fig. 3. Test environment and M candidate AP locations

B. Planning results

Three test scenarios have been defined as follows:

- $f = 0.5f_{cov} + 0.5f_I$ (test 1)
- $f = 1/8f_{cov} + 1/8f_I + 3/4f_{QoS}$ with a minimum throughput per user of $D^*_{(i,j)} = 256$Kbits/s (test 2) and $D^*_{(i,j)} = 512$Kbits/s (test 3).

Table I presents the values of the evaluation criteria for each of the three solutions found and the number of access points N planned. For the fist test, f_{QoS} has been computed for $D^*_{(i,j)} = 256$Kbits/s and a distribution of 100 users. The last columns of this table provides the search time T and the number of solutions N_s tested before convergence. It can be inferred from this table that the average time for planning such an environment is of only a couple of minutes. The more criteria are added or the more APs are needed, the longer the computation lasts. For each instance, it took about 6 minutes to compute the 257 coverage maps before launching the Tabu search. This order of magnitude for the search time is relevant for a competitive planning tool.

The performance of the solutions can be evaluated by the figures presented in Tab. II. For each solution, the following data is available:

- the percentage P_{cov} of surface area covered with $F^{BS}_{(i,j)} \geq S_1$,
- the percentage P_O of surface area where the interference constraint is fulfilled ($F^2_{(i,j)} \leq S_N$),
- the percentage P_I of surface area where there is no interference after channel assignment.
- the percentage P_{QoS} of surface area where the QoS constraint is fulfilled ($d_{(i,j)} \geq D^*_{(i,j)}$).
- the mean throughput per user value d_m.

The FAP algorithm we have developed is also based on a Tabu metaheuristic and is detailed in [21].

For test 1, P_{QoS} is given for $D^*_{(i,j)} = 256$Kbits/s. The basic coverage and non-interfering criteria allow by themselves to achieve the requested per-user throughput on 23% of the surface area. The use of the QoS criterion helps in providing the target QoS on a larger surface area (61%). This improvement is the best one obtained without drastically increasing interference levels by adding more APs for the given weighting coefficients. Besides, the higher the minimal per-user throughput is, the higher the number of APs and the smaller the service areas are, as presented on Fig. (4). The number of APs is the result of a trade-off between the QoS and the non-interfering criteria as they both try to respectively increase and decrease the number of APs.

In test 3, it is the throughput constraint that is favored during the search. The strict overlapping constraint is only fulfilled for 18% of the environment but the FAP algorithm was still able to completely avoid interference. On figure (4), the APs of test 3 are placed by pairs due to the acceptance of $h = 1$ interferer. By this way, it is possible to increase throughput without degrading the link quality. The weakness of this approach is that these pairs of APs create cells that are parceled out. Such cells present more bounds and thereby increase the occurrence of channel changes for the user. We think that it would be worth introducing a connexity criterion as already proposed in [16] for cellular networks.

Increasing throughput without degrading f_I may be achieved by introducing variable transmitting powers in the planning process. This feature would lead to smaller service areas, as required by high QoS constraints.

A delicate choice is to set the weighting coefficients of the aggregated evaluation function to get the desired trade-off between both QoS and interference criteria. There is no linear relation between the values of these coefficients and the observed trade-off. Gradient and order of magnitude of the criteria also influence the search, which makes the setting of the coefficients more difficult. For the instances presented, the weighting coefficients have been chosen empirically, after several launches. We are currently investigating multiobjective

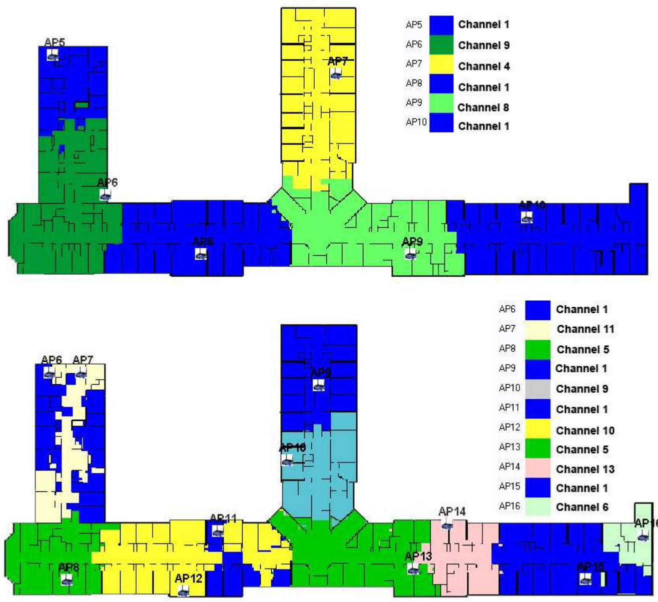

Fig. 4. Service areas and channel allocation for the solutions obtained with test 2 (top) and test 3 (bottom)

algorithms to prevent these multiple launches. The main feature of these algorithms is to provide the expert a set of solutions reflecting several trade-offs between the criteria.

VI. Conclusions and perspectives

In this paper, a new QoS constraint has been proposed to plan wLAN with guaranteed throughput. This constraint is added to the more usual coverage and non-interfering constraints in an aggregate function minimized with Tabu search. Each step of the method has been experimentally assessed (propagation simulations, Markov chain model, Tabu algorithm), but the final optimized network has not been yet. Nevertheless, simulation results show clearly the impact of the QoS constraint. The QoS constraint has been defined with a Markovian model. In this model each cell is considered independently. However a second radio parameter p_i has been introduced in the performance model to take the error probability induced by interferences into account. But this interference level has been assumed homogeneous and is chosen independently of the FAP result. If p_i is kept low, it represents an expected interference level and then the achieved QoS is an upper-bound. During the planning phase, the QoS is maintained high and interference low by the additional non-interfering constraint. This constraint allows to improve the frequency assignment under severe co-channel interference constraints. In our approach, a second tabu search, not detailed herein, was used to assign a channel to each selected AP *a posteriori*.

The QoS and interference avoidance planning approach proposed in this paper can of course be applied to any kind of indoor environment. The problem instances can become more complex. For instance, network planning in multi-level buildings or on larger surface areas, when more APs are needed, can be done. This approach doesn't look for the smaller amount of APs to deploy, but its main goal is to remain interference level low while providing throughput guaranty.

The relative weighting between non-interfering and QoS constraints is probably a good way to manage the interference level. We are currently investigating the use of multiobjective optimization algorithms providing several solutions representing a wide range of trade-offs between the 3 criteria defined above. From this set of solutions, a more global evaluation can be performed, allowing to select the best solution.

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