Integrated Access Point Placement and Channel Assignment for Wireless LANs in an Indoor Office Environment

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Abstract— **Wireless Local Area Network (WLAN) is currently among the most important technologies for wireless broadband access. The IEEE 802.11 technology is attractive for its maturity and low equipment costs. The overall performance of a specific WLAN installation is largely determined by the network layout and the radio channels used. Optimizing these design parameters can greatly improve performance.**

In this paper, access point (AP) placement and channel assignment are optimized using mathematical programming. Traditionally, these decisions are taken sequentially; AP placement is often modeled as a facility location problem, channel assignment as an (extended) graph coloring problem. Treating these key decisions separately may lead to suboptimal designs. We propose an integrated model that addresses both aspects simultaneously and thereby balances the two optimization objectives. Computational results show that indeed the integrated approach is superior to the sequential one.

I. Introduction

Wireless telecommunication has been gaining importance over the past years. In order to work properly and to exploit their full potential, wireless networks need to be planned carefully. The main goal of radio network planning is to provide widely available wireless service of high quality at a reasonable price. Other aspects such as security or emission reduction may also play a role. A prominent scheme for broadband wireless access is *Wireless Local Area Networks* (WLANs) based on IEEE 802.11 technology [12]. Only few design decisions have to be made in the case of WLANs. The most important ones are *positioning of access points* (APs) and *channel assignment.* A number of heuristic approaches for taking these design decisions are described in the literature. One common, but major drawback of such approaches is their inability to provide information on how much better an alternative design might be.

In this article, we first recall standard optimization models that address the two issues separately. For positioning APs, coverage planning models are fairly effective and can often be solved to optimality. Frequency assignment has been studied extensively, for example, in the context of GSM network planning [1]. The channel assignment problem belongs to the hardest problems in wireless network design. But due to a small number of available channels in IEEE 802.11 technology, the problem is still within reach of integer programming techniques. We show how the individual models can be merged into a complete optimization model for WLAN planning. This model allows to fathom the trade-off between high throughput and little cell overlap. In a case study based on realistic data for an indoor office environment, optimal network designs are computed with respect to the integrated model. We demonstrate how emphasis on maximizing throughput or on avoiding overlap changes the structure of the resulting solution.

A. Contributions

The contributions of our work are the following. First, we present optimization models that can be used for the two-step sequential planning of WLANs. For the first step, we give a model for optimizing the maximum expected throughput in the network by choosing proper locations for a given number of APs. For the channel assignment step, we suggest two models, one of which minimizes the co-channel overlap and the other one minimizes co-channel and adjacent channel interference. The first channel assignment model implies the use of a set of mutually non-overlapping channels, whereas the second model can also deal with overlapping channels.

Second, we combine the models for sequential planning into a model that allows us to jointly optimize the AP locations and the channel assignment (according to given priorities for each of the optimization goals). It is important that the model does not imply the knowledge of user distribution.

Third, we use a realistic scenario in a multi-floor office environment originated from a real Wireless LAN in an office building of Zuse Institute Berlin (ZIB) and present numerical results for the combined model comparing them to those obtained by the two-step sequential optimization. The solution patterns allow us also to derive ad hoc strategies, or guidelines, for WLAN planning and optimization for similar environments.

B. Related Work

General methods and modeling techniques for radio network design and optimization (also treating the problems studied here) can be, for example, found in [11], [22]. In [22], an

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integrated model for frequency planning and base station positioning is presented. However, the specialties of WLAN technology are not addressed and exploited in these general contributions.

AP positioning alone is studied in [16] with the goal of coverage maximization using heuristic methods. In [4], a hyperbolic objective function is used to account for the medium access contention while placing APs. Channel assignment and frequency planning have been extensively covered for other technologies [1], notably GSM. An adaption to IEEE 802.11 technology is suggested in [20]; interference and contention are modeled in a detailed manner, and solutions are found heuristically. Implementation issues for distributed dynamic channel assignment in wireless networks are discussed in [23], [26].

Channel assignment and AP placement are treated jointly in some works. However, channel assignment has in general only been posed in the form of a feasibility problem. For example, in [24], coverage maximization is complemented by simultaneously checking for a valid channel assignment in a mathematical programming model. Greedy strategies for first finding AP locations and subsequently assigning channels are used in [27]. A greedy strategy for deciding both aspects simultaneously with fairness considerations is proposed in [21]. In [3], tabu search is used for designing a fixed wireless access network, where channel assignment is considered jointly with AP positioning, among others. In [19], utilization of the most loaded "bottleneck" AP is minimized while a feasible channel assignment has to be found. The problem of modeling and minimization of contention under CSMA/CA-type protocols is addressed in [28]. The authors apply the integer programming approach to solve the problem for small networks, but have to resort to heuristics in order to deal with larger instances.

II. Technical Background

WLAN interfaces can work in *ad-hoc mode* or in *infrastructure mode*. In the former mode, mobile devices communicate directly with each other. In the latter one, APs are typically connected to a fixed network and act as source or destination of all radio links. In the following, mobile end systems are called *terminals*, while both APs and terminals are also denoted as *stations*. Stations can either negotiate medium access among themselves (*distributed coordination function*, DCF), or an assignment regime is implemented by the AP (*point coordination function*, PCF). Two specifications of the IEEE 802.11 standard are most relevant today: IEEE 802.11b and the more recent IEEE 802.11g. In both cases, transmission takes place in the unregulated ISM band at 2.4 GHz. In this paper, we consider IEEE 802.11g networks operating in infrastructure mode using DCF. This is a typical configuration for office environments.

A. Data Rate and Throughput

The IEEE 802.11g standard [12] specifies *adaptive rate selection* by which the coding scheme and the amount of redundancy are varied according to the connection quality. The maximum data rate is 54 Mbps. If signal quality is bad, fall-back rates down to 6 Mbps are selected. In addition, IEEE 802.11b is a fall-back option adding transmission rates down to 1 Mbps. The exact data rates and the received sensitivity thresholds defined by the AP hardware [7] are indicated by the solid line in Fig. 1. Signal quality is good and few retransmissions are needed in case a terminal is "close" to the next AP. This can be influenced by network planning.

Net Data-Rate Measurements. We observe the *net throughput* from simple measurements in an office building. The network performance tool NETIO [25] is used to measure the average downlink data throughput for several TCP streams with only one active user. The signal strength is measured with the WLAN hardware's performance monitor software, see Fig. 1 for results. In accordance with other publications, e.g., [17], the net throughput is significantly lower than the raw data rate due to protocol overhead and retransmissions. Moreover, the throughput gradually declines with decreasing received signal power.

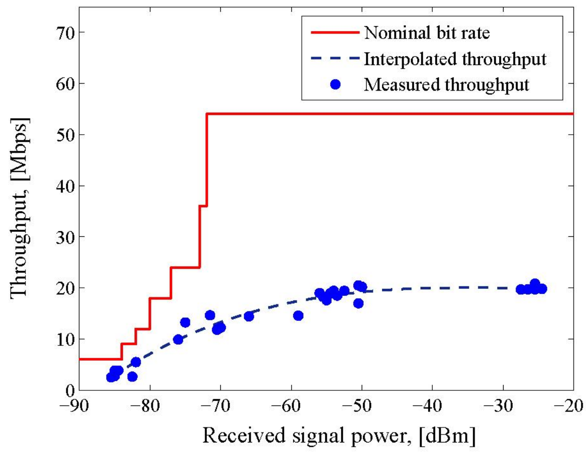


Fig. 1. Nominal and net throughput vs. received signal power.

B. Medium Access

Several terminals that want to communicate with an AP have to contend for the medium via a CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) mechanism. Prior to transmitting data, a station first senses the channel. If any activity is detected, the station backs off for a random time period and then retries. Otherwise, transmission starts. The receiver acknowledges proper reception of the payload. If two stations sense an idle channel and start transmitting (almost) at the same time, the transmissions collide and are lost. In reaction to a lacking reception acknowledgment, the transmissions are repeated after independently drawn random back-off time periods.

A four-way-handshake with RTS/CTS (Request To Send/Clear To Send) signaling packets can optionally be used to decrease the probability of collision (and to mitigate the "hidden terminal" and the "exposed terminal" situations). Short RTS and CTS signaling messages are used to reserve the medium. Hence, less data is lost upon collision. For a

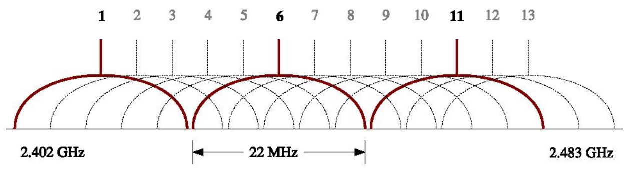


Fig. 2. Three non-overlapping channels for IEEE 802.11g.

single AP, all users are equally likely to gain access to the medium [5]. In combination with adaptive rate selection, this leads to all users' throughput dropping to the minimum if one "bottleneck" user is present [10].

C. Channel Assignment

IEEE 802.11g uses spectrum around 2.4 GHz that is divided into 13 channels with center frequencies 5 MHz apart [13]. (Channel availability varies across geographical regions due to different spectrum regulations.) In addition to the center frequencies, the standard specifies a power envelop by which the signal must drop by at least 30 dB below peak energy at ± 11 MHz and by at least 50 dB at ± 22 MHz from the center frequency.

Channels being at least 24 MHz apart are often considered to be non-overlapping. This yields at most three non-overlapping channels, i.e., channels 1, 6, and 11 (see Fig. 2). Therefore, channel assignment for IEEE 802.11g Wireless LANs is usually understood as a frequency assignment problem with three available frequencies. However, this view is simplified. First, a powerful transmitter operating on channel 1 can effectively interfere to those operating on channel 6 or even channel 11 [2]. Second, three channels are insufficient for WLANs with high stations density [26]. Third, not all the channels are available over the world due to the regional regulatory restrictions. Furthermore, the set of available channels can be reduced in some local environments. For example, the set of channels at some APs can be negotiated between administrators of neighboring networks. To resolve these issues, a realistic channel assignment model for WLANs planning must be flexible in choosing a set of available channels and must be able to consider solutions with overlapping channels.

D. Differences between IEEE 802.11b and IEEE 802.11g

The differences between IEEE 802.11b and IEEE 802.11g are not relevant as far as this work is concerned. IEEE 802.11b specifies an additional radio channel (for Japan), but the number of non-overlapping channels does not increase beyond three. Furthermore, IEEE 802.11b employs different coding schemes that offer data rates between 1 Mbps and 11 Mbps.

III. System Model

A. System Representation and Planning Problem

Given a fixed amount of AP equipment and a set of available channels, we aim for designing an efficient network plan for a WLAN such that maximum wireless coverage of a specified area is achieved. The efficiency of a network plan is defined by a channel overlap measure and the net throughput expected over the wireless service area for a single user.

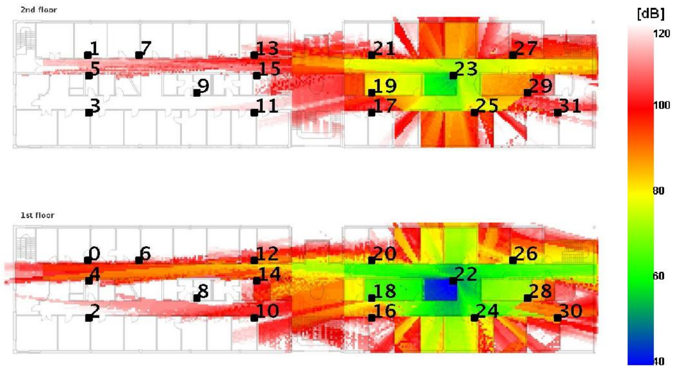


Fig. 3. Candidate APs locations and path-loss prediction for candidate AP 22.

Let $\mathcal{A}$ be the set of *candidate AP locations*, and let M ($0 < M \leq |\mathcal{A}|$) denote the maximum number of APs to be positioned. The candidate locations are determined in advance with respect to different factors such as potential installation costs, accessibility, physical security, radio propagation aspects, health safety, psychological factor (e.g., not all people are willing to have an AP installed in their office), etc.

The service area is represented by a grid of *test points* (TPs) with a given resolution. Let $\mathcal{J}$ denote the set of TPs to be covered. The received signal strength at TP j depends on the transmission power level $p_a^{(\mathrm{AP})}$ at the serving AP a and attenuation γ_{aj} between the AP and TP j. Received signal strength can be calculated as

$$p_{aj}^{(\mathrm{rec})} := \gamma_{aj}\, p_a^{(\mathrm{AP})}.$$

The transmission power $p_a^{(\mathrm{AP})}$ is assumed to be fixed and known in advance. The attenuation γ_{aj} between a candidate AP and each TP is given in a path-loss prediction grid. The set of candidate AP locations for the case study and path-loss predictions (obtained by a ray-tracing model) for an AP are shown in Fig. 3.

B. Performance Measures

The following performance figures are used to assess the quality of a given network design.

1) Coverage: A TP j ($j \in \mathcal{J}$) is *covered* if there is installed at least one AP a ($a \in \mathcal{A}$) such that the received signal from a satisfies $p_{aj}^{(\mathrm{rec})} \geq \theta^{(\mathrm{r})}$, where $\theta^{(\mathrm{r})}$ is the *receive sensitivity threshold*. The parameter $\theta^{(\mathrm{r})}$ defines the minimal signal strength required for receiving transmissions at the lowest possible data rate. The threshold is usually an adjustable configuration parameter and its typical values for a specific hardware can be found in the hardware documentation, e.g., in [7]. A network with (almost) complete coverage is desirable.

2) Net Throughput: To model net throughput, we use our measurements to find a polynomial fitting function (see Fig. 1) that represents the throughput experienced by a user in a contention-free environment. The throughput depends on the strength of the strongest signal received by any AP and hence – as we assume the transmit power to be fixed – on the attenuation value to this AP. Let this closest AP be denoted by a, then the net throughput user j is denoted by $\phi(\gamma_{aj})$. Low net throughput in some area is a strong indication of that a better AP placement is needed. Thus, one of our objectives amounts to maximizing the total net throughput over all TPs by choosing an appropriate subset of candidate AP locations.

3) Overlap: The second goal of our study is to optimize the channel assignment. In WLANs, the channels need to be assigned in a way that users and APs interfere with each other as little as possible and their contention for the medium in the network is minimized. This implicitly improves the network throughput. For the downlink direction, this can be achieved by minimizing the overlap of the coverage areas of APs operating on the same or adjacent channels. In uplink, user transmission would need to be taken into account as well, but this is beyond the scope of this paper.

To model coverage overlap, we use an *energy detection threshold* $\theta^{(d)}$ defining the minimum received signal power for sensing the channel as "busy." For a covered TP, there is (at least) one AP a with $p^{(rec)}_{aj} \geq \theta^{(r)}$. Suppose that a provides the strongest signal, then the number of overlapping APs is the number of APs b other than a that transmit on the same channel with $p^{(rec)}_{bj} \geq \theta^{(d)}$. Typically, we have $\theta^{(d)} \ll \theta^{(r)}$, i.e., the energy detection threshold is much lower than the receive sensitivity threshold. Therefore, a station which is farther away from a sending station than the intended receiver might still be restrained from sending to any other station if both stations operate on the same or overlapping channels.

IV. Optimization Models

Our goal in WLAN planning is to maximize the net throughput that a user can expect. Two aspects need to be considered: the connection quality at the physical layer (data rate) and contention for the medium with other users. The first aspect depends on AP locations: a user experiences a higher throughput if the serving AP is closer to the user (in terms of attenuation). The second aspect, contention among users, depends on the active users, the serving APs, and the channel assignment.

We first treat both aspects individually. That is, we separate AP placement (Section IV-A) from channel assignment (Section IV-B). An integrated optimization model is developed in Section IV-C.

A. Access Point Placement

Depending on the configuration of the APs, a TP can be serviced by at least one AP (*covered*) or none (*uncovered*). From the optimization stand point, pure coverage problems are viewed as *set-covering* problems [6]. Two basic variants are common, a) maximizing the covered area with a limited number of APs, or b) minimizing the number of APs needed to attain a certain degree of coverage (some percentage of the total area). Models of this type can be solved for very large instances using integer programming techniques.

The AP placement determines the maximum net data rate that a user can expect. With growing distance to the closest AP, the net data rate decreases as indicated in Section II-A. The maximum possible data rate is only achieved if a user does not have to contend for the medium. Under this assumption, maximizing the average net data rate taken over all TPs allows us to maximize the expected user's throughput. This problem can be seen as a *capacitated facility location* problem, which is extensively studied in Operations Research literature [8].

Integer programming model. We now model the problem of maximizing the expected throughput with at most M installed APs. Following typical facility location models, we use two classes of binary variables: variables $z_a \in \{0,1\}$ for all potential locations in $\mathcal{A}$, and variables $x_{aj} \in \{0,1\}$ for all pairs of locations and TPs. Here, $z_a = 1$ encodes that an AP is installed at location a. Furthermore, $x_{aj} = 1$ means that TP j is associated to AP a. (Note that variable x_{aj} can be explicitly set to zero, if the received signal strength in TP j from AP a is below receive sensitivity threshold $\theta^{(r)}$.) With these variables and the notation introduced in Section III, an integer programming model for maximizing the throughput can be stated as follows.

$$
\begin{aligned}
\max \quad & \frac{1}{|\mathcal{J}|} \cdot \textstyle\sum_{a,j} \phi(\gamma_{aj})\, x_{aj} & & \text{(1a)}\\
\text{s.t.} \quad & x_{aj} \leq z_a & \forall\, a,j \quad & \text{(1b)}\\
& \textstyle\sum_a x_{aj} \leq 1 & \forall\, j \quad & \text{(1c)}\\
& \textstyle\sum_a z_a \leq M & & \text{(1d)}\\
& z \in \{0,1\}^{\mathcal{A}},\ x \in \{0,1\}^{\mathcal{A}\times\mathcal{J}} & &
\end{aligned}
$$

The objective function (1a) measures the average throughput per TP. Constraint (1b) states that a TP can only be assigned to an AP if the AP is installed, (1c) ensures that each TP is assigned at most once, and (1d) limits the number of APs.

The optimization model (1) can quickly be solved to optimality for instances of the sizes we are interested in. Using state-of-the-art facility location algorithms [18] and refined models, however, much larger models can be solved. The tractability depends only on the number of "facilities" $|\mathcal{A}|$. For virtually arbitrary many "clients" $|\mathcal{J}|$, the problem can be solved for tens of thousands of facilities.

B. Channel Assignment

There are two ways of addressing channel assignment for WLANs. The simple one views channel assignment as a *coloring problem*, e.g., [19], [23]. Three non-overlapping channels are assumed, e. g. channels 1, 6, and 11 as in Fig. 2. In any channel assignment, the three channels are assumed to be interchangeable, as only the set of stations on the same channel generates *co-channel interference.* This symmetry among the frequencies is a potential obstacle to solving coloring problems with integer programming methods. In our first channel assignment model, which we present in Section IV-B.2, the symmetry is eliminated at a moderate cost in model complexity. The utilized modeling approach has shown to be very efficient when the number of colors/frequencies is fixed and very small.

As pointed out in Section II-C, ignoring adjacent channel interference is a significant simplification. A more realistic model accounts for both co- and adjacent-channel interference. The corresponding model is presented in Section IV-B.3.

Note that the two channel assignment problems are to be solved for a given set of M installed APs (let it be denoted by $\bar{\mathcal{A}}$).

1) Overlap estimation: The actual number of overlapping APs at a given TP depends on the AP placement and the channel assignment in the network. For optimization, we use an approximation of the overlap between two APs that can be computed by considering only *pairs* of APs. An overlap coefficient ν_{ab} represents the estimated size of the coverage overlap area of two APs a and b (in number of TPs) if tuned to the same radio channel. It is computed as

$$\nu_{ab} = \big|\{j \in \mathcal{J} : \\ \min\{p_{bj}^{(\mathrm{rec})}, p_{aj}^{(\mathrm{rec})}\} \geq \theta^{(\mathrm{d})} \wedge \max\{p_{bj}^{(\mathrm{rec})}, p_{aj}^{(\mathrm{rec})}\} \geq \theta^{(\mathrm{r})} + \delta\}\big|.$$

Here, we count the number of TPs at which both APs are detectable and at least one is stronger than the minimum coverage threshold $\theta^{(\mathrm{r})}$ plus an additive margin δ. The parameter δ (chosen in the range of 10–20 dB) is introduced to avoid counting TPs that receive another signal stronger than both $p_{aj}^{(\mathrm{rec})}$ and $p_{bj}^{(\mathrm{rec})}$ and would hence not count as overlap.

2) Minimum co-channel overlap: In this model, a set of binary variables $w_{ab} \in \{0, 1\}$ is defined for any (unordered) pair of APs $\{a, b\} \in \binom{\bar{A}}{2}$. (Here $\binom{\bar{A}}{n}$ denotes the set of subsets of $\bar{A}$ with n elements.) If AP a and AP b operate on the same channel, the corresponding variable w_{ab} is one. The complete model reads as:

$$\begin{aligned}
\min \quad & \textstyle\sum_{ab} \nu_{ab} w_{ab} & & \text{(2a)}\\
\text{s. t.} \quad & \textstyle\sum_{\{a,b\}\subset H} w_{ab} \geq 1 & \forall\, H \in \tbinom{\bar{A}}{4} & \quad \text{(2b)}\\
& w_{ab} + w_{bc} \leq 1 + w_{ac} & \forall\, (a, b, c) \in \bar{A}^3 & \quad \text{(2c)}\\
& w \in \{0, 1\}^{\binom{\bar{A}}{2}} & &
\end{aligned}$$

The objective (2a) minimizes the overlap area of APs operating on the same channel. Constraints (2b) enforce that among any four APs there is at least one pair using the same channel (as only three channels are available). Constraints (2c) are triangle inequalities imposing transitivity of the relation "a transmits on the same channel as b, and b transmits on the same channel as c." This ensures proper accounting of overlaps.

We assign actual channels to APs with the following procedure. A feasible solution to (2) is viewed as a graph on the set of AP locations, where any two nodes a, b are adjacent if $w_{ab} = 1$. This graph has at most three connected components (due to (2b)), all of which are cliques (due to (2c)). We arbitrarily assign one of the three available channels to all APs in a connected component. Symmetry of colors/frequencies is completely eliminated in this formulation. The model is computationally tractable, because there are not too many constraints of type (2b) with three channels. For a growing number of channels, the number of these constraints grows exponentially. A comparable formulation is hence not suitable for GSM, where there are typically dozens of frequencies.

3) Minimum co-channel and adjacent channel interference: In the above model, the channel assignment is done once an optimal channel overlap map is found. Given a set of available channels (denoted by $\mathcal{C}$), the next model explicitly involves (binary) decision variables f_a^c defining which channel to use at which AP. If channel c is assigned to AP a, then $f_a^c = 1$. Let $\mathcal{D}$ denote the set of channel distances at which two channels interfere with each other. To take interference on adjacent channels into account, we introduce binary variables w_{ab}^d for each pair of APs (a, b) and each channel distance $d \in \mathcal{D}$. Here, $d = 0$ if two APs use the same channel. If APs a and b operate on two channels with the channel distance $d \in \mathcal{D}$, $w_{ab}^d = 1$. The complete formulation is as follows,

$$\begin{aligned}
\min \quad & \textstyle\sum_{ab} \sum_{d} \dfrac{\nu_{ab}}{(1+d)^k}\, w_{ab}^d & & \text{(3a)}\\
\text{s. t.} \quad & \textstyle\sum_{c} f_a^c = 1 & \forall a & \quad \text{(3b)}\\
& f_a^{c_1} + f_b^{c_2} \leq 1 + w_{ab}^d & \forall ab, |c_1 - c_2| = d & \quad \text{(3c)}\\
& w \in \{0, 1\}^{\binom{\bar{A}}{2}\times\mathcal{D}},\ f \in \{0, 1\}^{\bar{A}\times\mathcal{C}} & &
\end{aligned}$$

The objective (3a) minimizes the overlap areas while prioritizing solutions in which APs with large overlap are separated in the channel space as much as possible. We use parameter k ($k > 0$) to control the effect of adjacent channel overlap assuming that the importance of space separation of APs decreases if the channel distance increases. Even more, the correlation is linear when $k = 1$. To focus on the co-channel overlap and small channel distances, $k > 1$ should be chosen (we use $k = 2$ in our numerical experiments). Observe that the objectives of (2) and (3) are equivalent when $\mathcal{D} = \{0\}$. Constraints (3b) ensure that each installed AP is assigned exactly one channel. Constraints (3c) trace the channel distance for each pair of APs depending on the channels they use.

C. Integrated Models

The next two integrated models take both aspects, throughput and overlap, into account. There is obviously a trade-off between average throughput maximization and overlap minimization. Best throughput is achieved in areas with high AP density, in which overlap cannot be avoided. If, on the other hand, there is no overlap at all, then this necessarily entails coverage holes and areas with little throughput. Mathematically, we hence consider a multi-criteria optimization problem [9]. Optimal solutions under several objectives are characterized as those solutions, for which none of the objectives can be improved without worsening the value of another objective. These solutions are sometimes referred to as *Pareto-optimal* ones. Most computational approaches at finding optimal solutions of multi-criteria problems use a scalarization method to cast the problem back to a one-dimensional one. There are several methods for doing so; in this work we choose the *weighted sum* approach, as it requires least previous knowledge of the solution space. We hence introduce a trade-off parameter $\alpha \in [0, 1]$ to scale the two objectives and formulate our model.

1) AP placement and minimum co-channel overlap: The first model combines models (1) and (2) and ignores adjacent channel overlap. The models interact only in the objective and in one type of constraints:

$$\max \quad (1-\alpha)\sum_{a,j}\phi(\gamma_{aj})\, x_{aj} - \alpha\sum_{ab}\nu_{ab}w_{ab} \qquad (4a)$$

$$\sum_{\{a,b\}\subset H} w_{ab} \geq \sum_{c\in H} z_c - 3, \qquad \forall\, H \in \binom{\mathcal{A}}{4} \quad (4b)$$

(1b), (1c), (1d), (2c)

$$x \in \{0,1\}^{\mathcal{A}\times\mathcal{J}},\ w \in \{0,1\}^{\binom{\mathcal{A}}{2}}$$

The trade-off parameter α controls how heavily overlap is penalized. Overlap is only relevant for selected APs. This is reflected by coupling the two models in constraint (4b), a modified version of (2b). The right-hand side of (4b) is positive when all four APs are selected. As only three channels are available, the constraint imposes that at least two of the four APs are in conflict. Otherwise, the constraint is void.

Different choices of α will produce different optimal solutions; the choice is therefore delicate. The decision between different optimal solutions is out of scope of multi-criteria optimization and left to the decision maker (the network planner). We will investigate a number of values below.

2) AP placement and minimum co- and adjacent-channel interference: The second model combines models (1) and (3). This model allows using a set of mutually overlapping channels but penalizes assignments in which APs with large coverage overlaps operate on either the same or adjacent channels (a property inherited from (3)). This allows us to not only reduce the co-channels interference but also the interference on adjacent channels. Again, we use a trade-off factor α to shift the weighting between the two objectives:

$$\max \quad (1-\alpha)\sum_{a,j}\phi(\gamma_{aj})\, x_{aj} - \alpha\sum_{ab}\sum_{d}\frac{\nu_{ab}w_{ab}^{d}}{(1+d)^{k}} \qquad (5a)$$

$$\text{s.t.} \quad \sum_{c} f_a^c = z_a \qquad \forall a \qquad (5b)$$

(1b), (1c), (1d), (3c)

$$x \in \{0,1\}^{\mathcal{A}\times\mathcal{J}},\ w \in \{0,1\}^{\binom{\mathcal{A}}{2}\times\mathcal{D}},\ f \in \{0,1\}^{\mathcal{A}\times C}$$

The objective (5a) blends the objectives (1a) and (3a). AP selection is linked to channel assignment in (5b) by which a channel has to be assigned if and only if the corresponding AP location has been selected.

V. Computational Results

In this section, we present solutions to the optimization problems (4) and (5) on a test scenario for different values of the trade-off parameter α and discuss the impact of optimization and the parameter α on the difference performance measures introduced in Section III-B.

A. Planning Scenario and Computations

Our test network represents a part of the Wireless LAN deployed in the ZIB building. We fix 32 candidate AP locations for this two-floor scenario, see Fig. 3. The total number of APs to be installed shall not exceed eight. We assume that each AP is of type Cisco AP-1200/AP21G [7] and compliant with the IEEE 802.11g standard. Every AP is equipped with an omnidirectional antenna. The path-loss predictions are obtained for each candidate AP location for each of the two floors via 3D ray-tracing methods with multiple reflections using a 3D model of the building [14], [15]. (See Fig. 3 for a path-loss prediction example.) Table I presents test network statistics.

TABLE I

SCENARIO CHARACTERISTICS

Characteristic / Parameter	Value
Number of floors	2
Service area size in each floor [m×m]	84×18
Number of candidate locations $\lvert\mathcal{A}\rvert$	32
Maximum number of installed APs M	8
AP height above the floor [m]	2
AP antenna type	AIR-ANT-4941
AP antenna gain [dBi]	2
AP transmission power [mW]	30
Frequency band [GHz]	2.4
Channel Set	13 channels (ETSI), 2.412–2.484 GHz
Number of TPs	798
TP grid resolution [m]	2
TPs' height above the floor [m]	1
Energy detection threshold [dBm]	−115
Receive sensitivity threshold [dBm]	−90

The optimization models have been solved to optimality with ILOG CPLEX 10.0 on a standard PC (2.4 GHz Pentium processor, 2 GB RAM). The solution time for the facility location model (1) did not exceed 30 s. For the coloring models (2) and (3), the solution time was less than one second. Instances of the integrated model (4) could take a few hours to be solved to optimality. For the same set of channels (channels 1, 6, 11) and $\mathcal{D} = \{0, 5, 10\}$, the computing time for solving instances of the integrated model (5) was from one minute to one hour, depending on the parameter α (the longest computing times were observed when none of the two objectives significantly dominated the other, i.e., for $\alpha = \{0.4, 0.5, 0.6\}$).

Although we have been able to solve the problems to optimality for the given instance, it may be more practical to resort to efficient heuristics that are able to find good near-optimal solutions within a reasonable amount of time. This becomes especially important when larger networks are to be planned. A possible heuristic approach could be, for example, the one based on Lagrangian relaxation where, depending on the model, either constraints (4b) or (5b) are relaxed into the objective.

B. Results

For choosing relevant values of the trade-off parameter α, we first scale the two components of the objective function such that the values are on a comparable scale. We then varied α in steps of 0.1 in the interval $[0, 1]$ in both integrated models. Small values of α emphasize throughput maximization, while values close to 1.0 rather stress overlap minimization. For the extreme case $\alpha = 0$, we actually solved two optimization problems sequentially; this corresponds to the traditional scheme for network planning. The obtained solutions are also compared to the reference configuration representing the currently running network. The results are presented in Table II. In some intervals, different values of α lead to the same solution, so the referring columns are grouped. For each solution in Table II, we compute the objectives of models (1), (2), and (3). Note that although a combined objective involves the objective function (1) and either (2) or (3), for each combined model we do evaluate also the objective function which is not a part of the model; the corresponding values in the table appear in italic.

1) Performance: Our studies show that the performance of the (heuristically obtained) reference solution can be greatly improved. More interestingly, the influence of different optimization approaches on key performance figures and the interplay between these figures can be studied. The performance statistics discussed below are summarized in Table II.

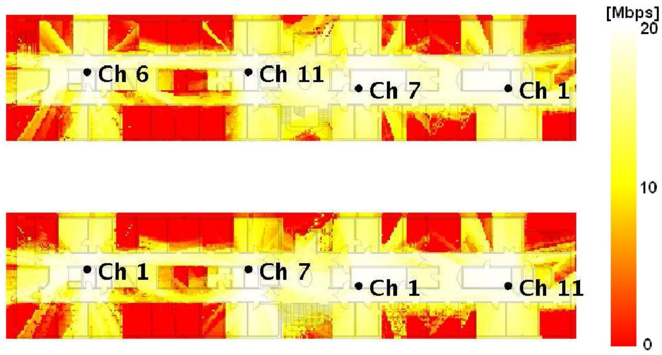
Coverage. While in the reference solution about 11 % of the planning area are left uncovered, most optimized configurations decreased this fraction to 2 % or below. This large improvement is mainly due to the fact that in the reference solution all APs were placed in the inner part of the building, where massive reinforced concrete walls obstruct the propagation. For higher values of the trade-off parameter ($\alpha \geq 0.8$), the uncovered area grows to 4 %.

Throughput. By using the facility location model, a significant improvement in average throughput is obtained. This is the visual impression from throughput plots over the area, Fig. 4. The reference configuration with an average throughput of 9.7 Mbps is shown in Fig. 4(a). Large areas with little average throughput (red patches) can be discerned. The first optimized configuration focusing on throughput is able to fill these gaps by properly interleaving the AP locations. The plot in Fig. 4(b) shows a far better connection to most points in the area. The average throughput increases up to 13.16 Mbps.

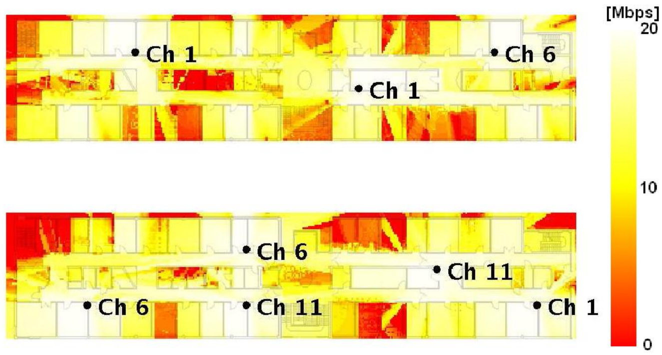
An interesting aspect here is that the integration of the facility location model leads to decent performance in terms of throughput also for higher α (see Table II). Up to $\alpha = 0.7$, throughput is hardly sacrificed when channel assignment is emphasized. Only beyond this point throughput degrades noticeably.

Overlap. The protocol aspects of IEEE 802.11 are evaluated in the upper part of Table II. The row "single server" indicates the fraction of the covered area with only one received signal satisfying the energy detection threshold, i.e, the signals received from all other APs are too weak to interfere with ongoing transmissions from the serving AP or to contend for the medium with it. The row "Overlap $\geq$ 1" indicates the fraction of the area where the second strongest received signal is also above the energy detection threshold. The row "Overlap $\geq$ 2" denotes a subset of the first overlap set and corresponds to the area with more than one potentially interfering APs. The last two areas are to be kept small to achieve high network performance.

The throughput-centered optimization ($\alpha = 0$) improves coverage, but the percentage of overlap remains virtually the same. The fact that overlap does not increase – even though the area is better covered – can be attributed to solving the channel assignment appropriately. When channel assignment and AP location decisions are integrated, however, best results are obtained. From about 40 % overlap for the reference configuration and the throughput-optimal configuration, the overlap can be reduced to below 20 % for higher values of α up to 0.8. Only for $\alpha \geq 0.9$, the overlap performance decreases again, as does throughput.



(a) Reference configuration



(b) Optimized ($\alpha = 0$)

Fig. 4. Impact of optimization on throughput, integrated model (4).

Comparing the obtained solutions for the two integrated models, we observe that even for the same AP placement, i.e., when the previously discussed performance metrics are the same, the models provide us with different channel assignments (see "Objective (3a)" in Table II). In particular, the channel distance for APs having large overlap area is decreased in the solutions obtained for the model (5) resulting in smaller values of (3a).

2) Some Resulting Configurations: We briefly analyze the features of typical alternative solutions. First, let us compare the reference configuration to those obtained by the first integrated model.

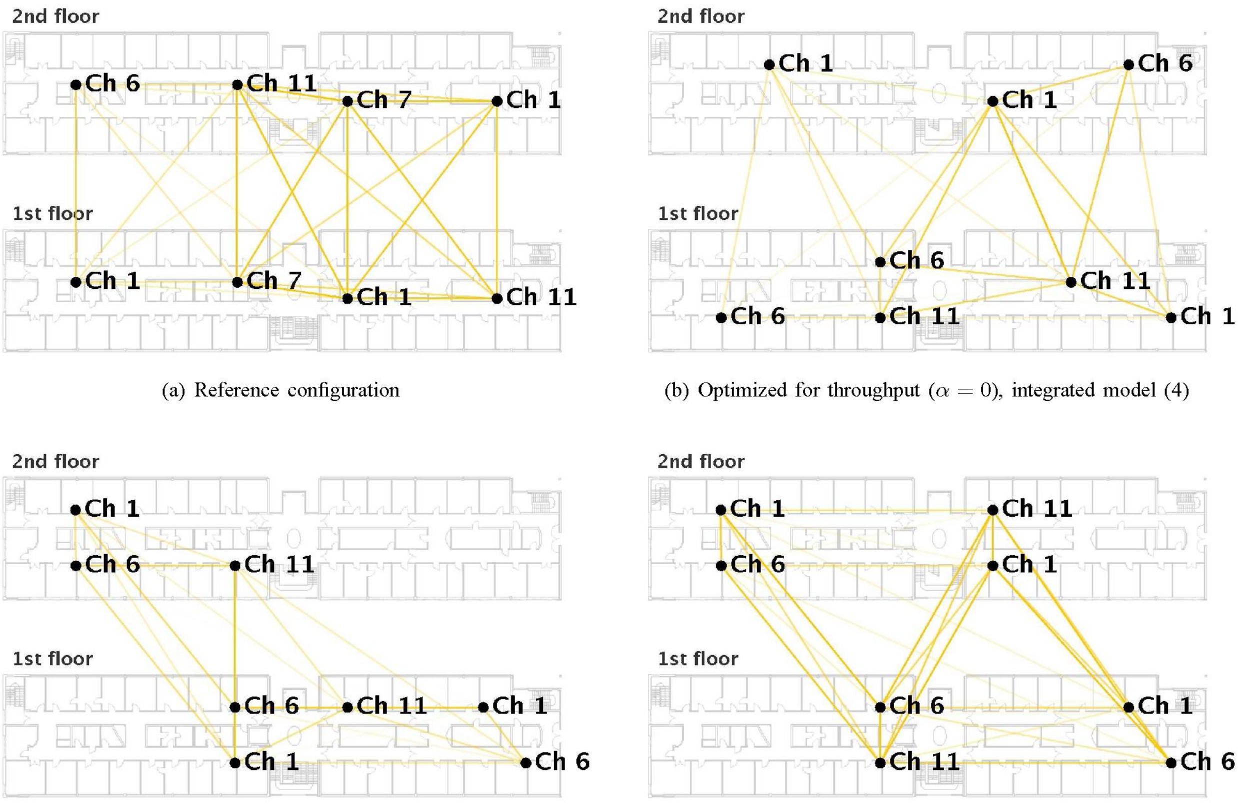
Reference configuration. The AP positions in Fig. 5(a) have been chosen mainly for practical reasons. The rooms in the center part of the building are not offices but infrastructure and service rooms. APs are hence kept safe from manipulation while being easily accessible for maintenance. Channels have been assigned in a circular fashion ensuring maximum channel separation for APs.

Throughput solution ($\alpha = 0.0$)**.** The APs are distributed in an interleaved fashion across the building. This is to best spread the signals in the area. No locations in the middle have been selected. This is mainly because the inner walls consist of massive reinforced concrete, which strongly attenuates radio signals.

TABLE II
PERFORMANCE OF DIFFERENT NETWORK DESIGNS

Performance metric		Reference scenario	Integrated model (4), various α							Integrated model (5), various α					
			0.0*	0.1 0.2	0.3 0.4 0.5	0.6 0.7	0.8	0.9	1.0	0.0*	0.1 0.2	0.3 0.4 0.5 0.6	0.7	0.8	0.9 1.0
Single server	[Area %]	47.57	60.74	66.82	77.73	78.44	78.26	77.64	72.38	60.74	66.82	77.73	78.44	76.75	72.38
Overlap ≥ 1	[Area %]	40.93	37.55	31.56	21.41	20.59	18.30	18.37	24.06	37.55	31.56	21.41	20.59	19.79	24.06
Overlap ≥ 2	[Area %]	4.00	3.50	4.52	5.18	4.55	3.74	3.99	3.43	3.50	4.52	5.18	4.55	4.43	3.43
Uncovered	[Area %]	11.50	1.71	1.62	0.86	0.98	3.44	3.99	3.56	1.71	1.62	0.86	0.98	3.45	3.56
Av. throughput	[Mbps]	10.69	13.16	13.16	13.10	13.06	12.66	12.41	12.19	13.16	13.16	13.10	13.06	12.52	12.19
Objective (1a)		10.84	13.30	13.28	13.15	13.03	12.55	12.33	12.16	13.30	13.28	13.15	13.03	12.46	12.16
Objective (2a)	$[\times 10^6]$	12.79	6.20	2.11	1.39	1.23	0.95	0.87	0.87	*6.20*	*2.11*	*1.39*	*1.23*	*0.95*	*0.87*
Objective (3a)	$[\times 10^6]$	13.77	*7.76*	*2.60*	*1.90*	*1.77*	*1.60*	*1.52*	*1.44*	6.92	2.56	1.88	1.76	1.43	1.38

* Sequential optimization



(a) Reference configuration

(b) Optimized for throughput ($\alpha = 0$), integrated model (4)

(c) Optimized for overlap ($\alpha = 1$), integrated model (4)

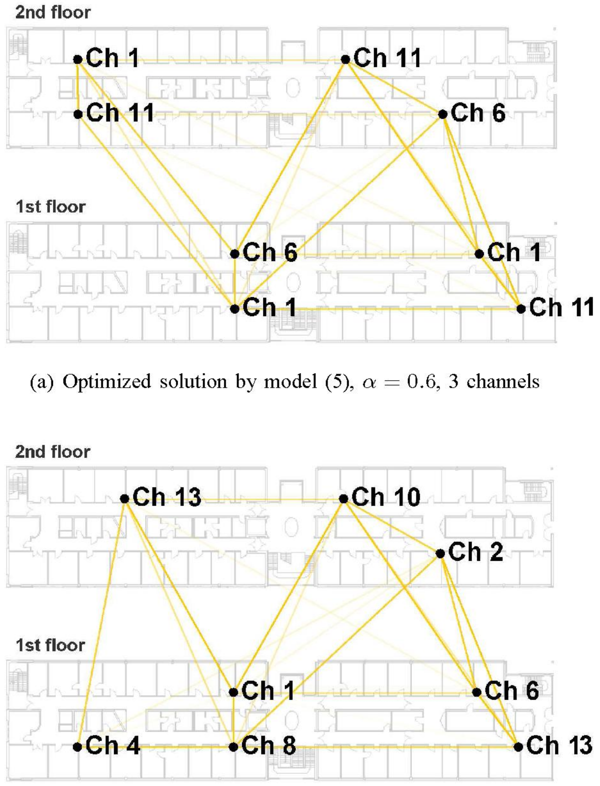
(d) Optimized for both ($\alpha = 0.6$), integrated model (4)

Fig. 5. AP positions and overlap for different network designs.

Overlap solution ($\alpha = 1.0$)**.** The configuration here can be interpreted as three groups of three APs (with one AP belonging to two groups). Within a group, three different channels are assigned. This formation is the logical consequence of overlap minimization if three frequencies are available.

Compromise ($\alpha = 0.6$)**.** If both aspects are weighed comparably, we still have groups of APs. However, the groups contain only pairs, and the four pairs are placed in an interleaved fashion for better coverage and throughput.

Fig. 6(a) presents an alternative solution obtained by the second integrated model for $\alpha = 0.6$ and the same set of three channels ($\mathcal{C} = \{1, 6, 11\}$) assuming that any two of the channels interfere with each other. Comparing to Fig. 5(d), we observe that in the alternative solution, the channels assigned to neighboring APs are better spaced while the AP locations remain the same in most cases. A small number of available channels and large overlaps between APs in the right part of the building have been also compensated by changing location of an AP. For $\alpha = 0.6$, we have also found a solution to the second integrated model when all 13 channels are available



(a) Optimized solution by model (5), $\alpha = 0.6$, 3 channels

(b) Optimized solution by model (5), $\alpha = 0.6$, 13 channels

Fig. 6. AP positions and overlap for different network designs.

and all the channels are mutually interfering. The solution is presented in Fig. 6(b).

C. Choice of α

Our experiment reveals that the traditional sequential decision process of first deciding on AP positions and then assigning channels can be outperformed by considering channel assignments issues already when deciding AP positions. The best mix of performance figures in our case is achieved when choosing α as 0.6 or 0.7. For these values, a significant reduction of overlap and contention can be achieved with only a marginal reduction of throughput. For higher values of α, solution quality degrades in all measures under examination. Visually inspecting solutions such as the one shown in Fig. 5(c) suggests that the optimization focusing exclusively on throughput produces "artefact" solutions that have no practical use. The decrease even in the overlap measures is only possible for and ultimately due to the fact that the overlap weights ν_{ab} in (4) and (5) are mere estimations of the expected overlap between two APs.

In practice, different values of α should be tested to find several candidates for a good compromise between the two conflicting objectives; our experiments are valid only for the specific dataset under consideration.

VI. Conclusions and Outlook

We have presented new optimization models for Wireless LAN planning for networks using the IEEE 802.11 infrastructure mode. In this context, the most important decisions to be made are AP location and channel assignment. Practical planning approaches usually take heuristic decisions or handle both aspects sequentially. After a careful analysis of the system's properties and protocols, we have chosen two aspects to be addressed in our work. First, the best possible net throughput a user can obtain depends on the absolute strength of the serving access point's signal. Second, if the channel has to be shared among several users, the data rate is shared among several users and further decreased due to the contention mechanism used in the IEEE 802.11 protocol family.

The first aspect can be modeled as a facility location problem. For minimizing contention, it is important to reduce overlap between stations served by different APs at the same frequency. We have presented two models for finding good channel assignments. The choice of the model depends on whether the adjacent channel overlap is to be taken into account. The central contribution are integrated models that allow us to decide on AP locations and channel assignment simultaneously. Moreover, by using a trade-off parameter the relative priorities of the two optimization goals can be controlled. Different choices of the parameter allow the network planner to explore different compromise solutions and choose between them.

A computational study based on realistic data has shown that the integration of both aspects can provide a noticeable performance improvement in comparison to the common sequential scheme. When considering AP location and channel assignment jointly in a well-balanced way, a substantial reduction of channel overlap can be "bought" for a hardly noticeable reduction in throughput or coverage.

With these encouraging results, the next step is to verify our findings in a larger planning scenario with more detail data. We expect the main findings to carry over. For providing stronger evidence for the impact of our optimization scheme on performance, a refined system model including "uplink" contention and possibly simulation of the medium access protocol is necessary.

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References

[1] K. Aardal, S. V. Hoesel, A. M. C. A. Koster, C. Mannino, and A. Sassano. Models and solution techniques for frequency assignment problems. *Oper. Res. Quart.*, 1(4):261–317, Dec. 2003.

[2] A. Adya, P. Bahl, R. Chandra, and L. Qiu. Architecture and techniques for diagnosing faults in IEEE 802.11 infrastructure networks. In *Proc. of the 10th Annual International Conference on Mobile Computing and Networking*, pages 30–40, Sep. 2004.

[3] S. Allen and R. Taplin. Automatic design of fixed wireless access networks. *Mob. Network Design and Innovation*, 1(1):1–7, 2005.

[4] E. Amaldi, A. Capone, M. Cesana, L. Fratta, and F. Malucelli. Algorithms for WLAN coverage planning. *Springer LNCS*, 3427:52–65, Feb. 2005.

[5] G. Bianchi. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE J. Sel. Area Comm.*, 18(3):535–547, 2000.

[6] A. Caprara, M. Fischetti, and P. Toth. Algorithms for the set covering problem. *Annals of Operations Research*, 98:353–371, 2000.

[7] Cisco Systems, Inc., http://www.cisco.com/en/US/products/hw/wireless/ps430/. *Cisco Aironet 1200 Series Access Points, Data sheet.*

[8] G. Cornuejols, R. Sridharan, and J. M. Thizy. A comparison of heuristics and relaxations for the capacitated plant location problem. *European J. Oper. Res.*, 50(3):280–297, Feb. 1991.

[9] M. Ehrgott. *Multicriteria Optimization*. Springer, 2nd edition, 2005.

[10] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda. Performance anomaly of 802.11b. In *Proc. INFOCOM 2003*, San Francisco, CA, 2003.

[11] S. Hurley. Planning effective cellular mobile radio networks. *IEEE Trans. Veh. Technol.*, 12(5):243–253, 2002.

[12] IEEE. IEEE Std 802.11–1997: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 1997.

[13] IEEE. IEEE Std 802.11g–2003 (amendment to IEEE std 802.11): Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 2003.

[14] J. Jemai, R. Piesiewicz, and T. Kürner. Calibration of an indoor radio propagation prediction model at 2.4 GHz by measurements of the IEEE 802.11b preamble. COST 273 TD, Duisburg, Germany, 2002.

[15] J. Jemai and U. Reimers. Channel modeling for in-home wireless networks. In *Proc. ISCE02*, Erfurt, Germany, 2002.

[16] M. Kamenetsky and M. Unbehaun. Coverage planning for outdoor wireless LAN. In *Proc. IZS2002*, Zurich, Switzerland, 2002.

[17] A. Kamerman and G. Aben. Throughput performance of Wireless LANs operating at 2.4 and 5 GHz. In *Proc. PIMRC2000*, London, UK, 2000.

[18] A. Klose and A. Drexl. Lower bounds for the capacitated facility location problem based on column generation. *Management Sci.*, 51(11):1689–1705, Nov. 2005.

[19] Y. Lee, K. Kim, and Y. Choi. Optimization of AP placement and channel assignment in wireless LANs. In *Proc LCN'02*, Tampa, FL, 2002.

[20] K. K. Leung and B.-J. Kim. Frequency assignment for IEEE 802.11 wireless networks. In *Proc. VTC 2003-Fall*, Orlando, FL, 2003.

[21] X. Ling and K. L. Yeung. Joint access point placement and channel assignment for 802.11 wireless LANs. In *Proc. WCNC 2005*, New Orleans, LA, 2005.

[22] R. Mathar and M. Schmeink. Optimal base station positioning and channel assignment for 3G mobile networks by integer programming. *Ann. Oper. Res.*, (107):225–236, 2001.

[23] J. Riihijärvi, M. Petrova, and P. Mähönen. Frequency allocation for WLANs using graph colouring techniques. In *Proc. WONS'05*, St. Moritz, Switzerland, 2005.

[24] R. C. Rodrigues, G. R. Mateus, and A. A. F. Loureiro. On the design and capacity planning of a wireless local area network. In *Proc. NOMS2000*, Honolulu, Hawaii, 2000.

[25] K. U. Rommel. NETIO benchmark, version 1.26. http://www.ars.de/ars/ars.nsf/docs/netio, 1997–2005.

[26] E. G. Villegas, R. V. Ferré, and J. P. Aspas. Implementation of a distributed dynamic channel assignment mechanism for IEEE 802.11 networks. In *Proc. PIMRC 2005*, September 2005.

[27] P. Wertz, M. Sauter, G. Wölfle, R. Hoppe, and F. Landstorfer. Automatic optimization algorithms for the planning of wireless local area networks. In *Proc.VTC2004-Fall*, Los Angeles, CA, Oct. 2004.

[28] F. A. Zdarsky, I. Martinovic, and J. B. Schmitt. On lower bounds for MAC layer contention in CSMA/CA-based wireless networks. In *Proc. DIAL M'05*, Cologne, Germany, 2005.