Planning of Large-Scale WLAN Infrastructures

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Abstract— **Network planning is a prerequisite for proper deployment of large-scale WLAN infrastructures.. In this paper, we consider the three most important issues for the proper network planning: propagation modeling, coverage optimization and channel allocation. For the propagation modeling, we modified the dominant path propagation technique to predict the coverage matrix by using the equivalent graph representation of the room structure and the shortest path algorithm for determination of the dominant paths. The coverage optimization is realized through a known optimization function, which maximizes the average signal quality and minimizes the area with poor signal quality. The channel allocation is optimized in terms of an objective function that maximizes the signal-to-interference ratio over the entire service area. Different combinations of simulated annealing, genetic and pattern search algorithms are used as optimization algorithms. Multiple deployment scenarios in our laboratory premises are studied in order to validate our design tool.**

Key words: WLAN, radio propagation modeling, coverage and channel allocation optimization, simulated annealing, genetic and pattern search algorithms

1. INTRODUCTION

Wireless LANs (WLANs) are already widespread in home and office environments and provide the best-effort services at high-data rates to the low mobile users [1]. Although initially deployed in small numbers and in ad-hoc fashion, the increase of the density of the Access Points (AP) in today's large-scale infrastructures necessitates the need for proper WLAN deployment [2]. Thus, the network planning is necessary in order to influence both the signal coverage and the co-channel interference in a given indoor environment, thus optimizing the overall network performance. The complexity of the network planning problem in a WLAN depends on the number of APs and operational channels [3]. It involves the use of propagation analysis, objective functions and optimization algorithms for determination of the optimal AP positions and channel allocation.

In this paper, we present our approach on planning of large-scale WLAN infrastructures, which include the study and implementation of all of the aforementioned network planning issues. It proposes a novel propagation algorithm for determination of the dominant path between any transmitter-receiver pair, which produces the coverage prediction matrix for any two-dimensional floor layout. We also derived an original approach to calculate the optimal AP locations by utilizing a well-known optimization function (OF) evaluated by sequential invocation of two different optimization algorithms. A practical approach for channel allocation optimization is also proposed, which maximizes the signal-to-interference ratio (SIR) in service area.

This article is organized as follows. In Section 2, we present our propagation model. The coverage planning and optimization is presented in Section 3, and the interference and channel allocation in Section 4. We conclude in Section 5.

2. RF PROPAGATION MODELING

The radio propagation modeling is very complicated and sensitive aspect of the wireless network planning. Either statistical/empirical models or ray-tracing models have been investigated to obtain accurate and fast propagation models of an indoor environment. However, the determination of few dominant paths for each transmitter-receiver pair usually provides sufficient accuracy since only 2 or 3 rays contribute for more than 95% of the received signal power. Therefore, we used the *Dominant Path Modeling*, which can be subdivided into two steps: 1) Determination of the dominant paths, and 2) Prediction of the path loss along these paths.

As shown in Figure 1, different rays may reach the receiver passing the same sequence of rooms and penetrating the same walls. The contributions of those rays, which offer the same number of interactions to the total field strength, are very similar (and grouped together to form the dominant path), while the other rays with more interactions can be neglected because of their higher attenuation.

Determination of the dominant paths in a given indoor environment requires information about the rooms' structure: wall coupling between a pair of neighboring rooms, association of the reference (grid) points to rooms where they belong and attenuation of each wall. The information about the wall coupling is used to compute the equivalent graph structure, where nodes represent the rooms and walls represent the links with unity metric. The dominant paths between a pair of nodes is determined by using the *k*-shortest path Dijkstra algorithm, i.e. by finding first *k* paths that traverse the smallest number of walls to connect any two grid points in a pair of rooms. For a given transmitter-receiver pair, those *k* paths are considered to be dominant and their respective powers are added to calculate the mean reception power. The mean attenuation of each path is calculated by adding the attenuation of each passing wall to the free-space path attenuation. The *path loss matrix* is generated for the entire indoor layout, based on the predicted mean attenuation in each grid point and for each possible AP location.

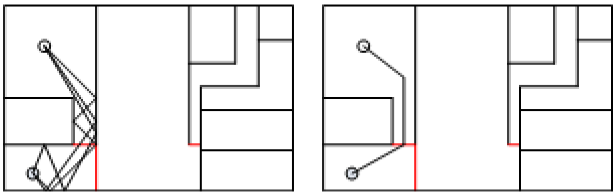

Figure 1: Representation of the multi-path: [left] possible rays [right] dominant path

We applied the dominant path approach to predict the path loss matrices in the Telecommunication Laboratory of the Ss. Cyril and Methodius University in Skopje. The prediction results are compared to the respective field measurements, which were realized by using in-house developed RF site-survey tool [9]. Both the prediction and the measurements are realized at potential receiver locations placed in the virtual rectangle grid (in this case, 6 x 9) over the 16x25m^2 laboratory floor layout.

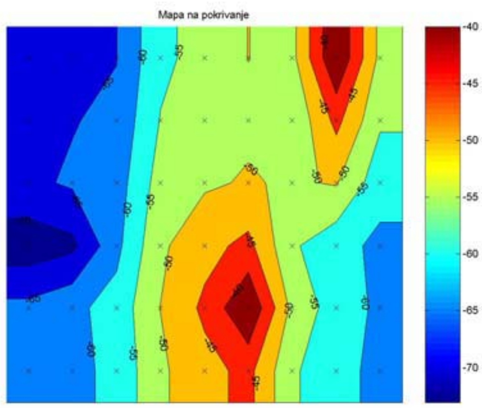

Figure 2: Coverage map obtained via Dominant path prediction for two APs at coordinates (1,8) and (5,6)

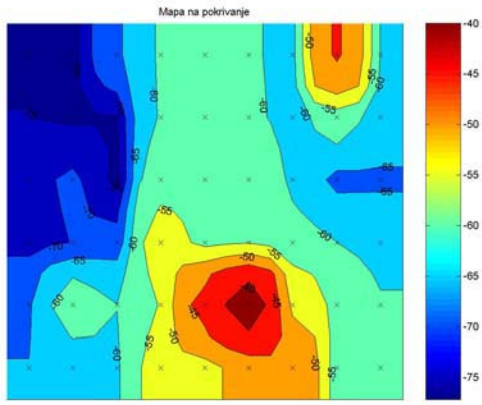

Figure 3: Coverage map obtained by experimental site survey measurements for two APs at coordinates (1,8) and (5,6)

Figures 2 and 3 depict both the predicted and measured coverage maps (AP transmit power reduced by the relevant path loss) for the deployment scenario in the laboratory represented by a pair of IEEE 802.11b/g APs. The APs are placed at grid coordinates (1,8) and (5,6) (with origin placed in the upper left corner of the layout). Note that the color-bar by each figure represents the mapping of the colors to the mean reception power expressed in dBm, assuming 5 dBm transmit power, 0 dBi omni-directional transmit and receive antennas and 10 dB (all identical) wall attenuations. Comparison of the large number of predicted and measured coverage maps for multiple deployment scenarios confirmed the high accuracy of our prediction model (less then 7% on the average).

3. COVERAGE OPTIMIZATION

For the matter of coverage optimization i.e. AP placement optimization we used the well-known objective function proposed in [3] and [7]. Two objectives should typically be achieved in coverage optimization: maximizing the average signal quality in the entire service area and minimizing the area with poor signal quality. These two objectives do not necessarily have the same set of optimal AP locations, so a suitable trade-off should be found. Thus, a weighted combination of two separate objective functions is used: a *minisum* and a *minimax objective function*. Maximization of the average signal quality is achieved by minimizing the average path loss over the entire service area. The second objective function is used to lessen the worst-case path loss by minimizing the contribution of grid (reception) points with a maximal path loss. Maximization of the average signal quality is achieved by evaluating and minimizing the average path loss f_1, expressed by:

$$f_1 = \frac{1}{M}\sum_{i=1}^{M}\left(g_i^k + \mu \max\left\{0, g_i^k - g_{\max}\right\}\right) \qquad (1)$$

over the entire service area. Here, M is the total number of reception points in the service area, g_i^k is the path loss from AP k in the i-th reception point and μ is the penalty factor. Each point is assigned to K APs and the minimum path loss is chosen, i.e.,

$$g_i^k = \min_{j=1,\ldots,K} \{g_i^j\} \quad \forall i = 1,\ldots, M \tag{2}$$

where K is the total number of APs. The term g_{max} defines the maximum tolerable path loss in reception point i. For receiver locations where g_i^k exceeds the threshold g_{max} a penalty term of $\mu(g_i^k - g_{\max})$ is added.

In order to lessen the worst-case path loss, an additional objective function should be used to minimize the contribution of points with maximal path loss:

$$f_2 = \max\left(g_i^k + \mu \max\left\{0, g_i^k - g_{\max}\right\}\right) \tag{3}$$

By combining (1) and (3) with the balancing parameter ψ, the final form of the objective function (OFc) that should be minimized is represented into the form:

$$OF_c = \psi \cdot f_1 + (1-\psi) \cdot f_2 \tag{4}$$

The parameter ψ is typically set within the range between 0.5 and 1, while we set $\psi = 0.6$ [3, 7] in our case studies, so the first term of the OFc is slightly emphasized. Additionally, gmax is set to 95dB.

The optimal location for a single AP can be obtained by evaluating the OFc for all possible AP locations by using the coverage prediction matrix as an input from the propagation model, and choosing the one with minimal OFc. Since the number of OFc evaluations increases linearly with the number of possible AP sites, the exhaustive search is not suitable to determine the global optimal solution. Hence, we used four types of heuristic algorithms for testing over the objective function OFc: pruning, simulated annealing (SA), genetic algorithms (GA) and pattern search (PS). The best results are obtained by sequential invocation of certain pairs of optimization algorithms (e.g. simulated annealing and pattern search algorithms denoted by SA+PS, or genetic algorithm and pattern search denoted by GA+PS). We found that the best trade-off between computation complexity and the standard deviation of the obtained results is achieved by using the SA+PS [10]. The SA is used to determine the initial solution set [8], while the PS is used for fine-tuning of the APs positions [7].

For the randomly selected initial AP positions, the SA+PS always converge towards the global optimum for the observed office floor layouts. The minimized value of the OF_c has a low standard deviation for each run of the SA+PS, which results in similar AP positions in each run of the SA+PS optimization. Figures 4 and 5 depict the convergence speed (in iteration cycles) for SA and PS algorithms, respectively, given M = 400 grid points, K = 5 APs.

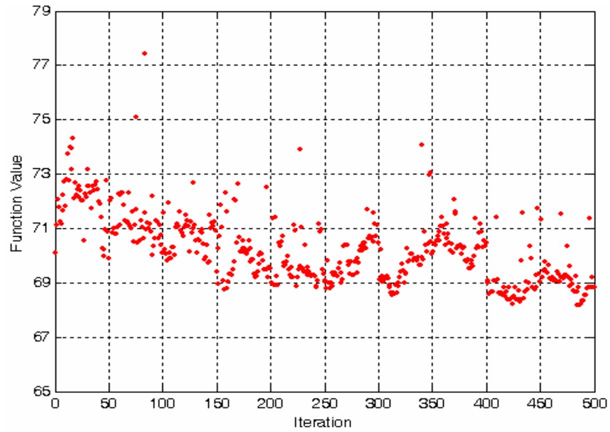

Figure 4: Simulated annealing (SA)

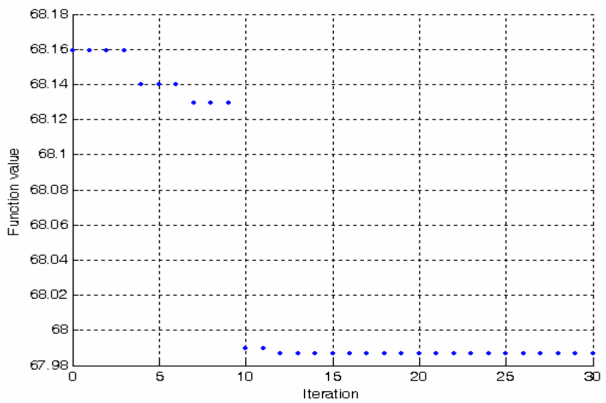

Figure 5: Pattern search (PS)

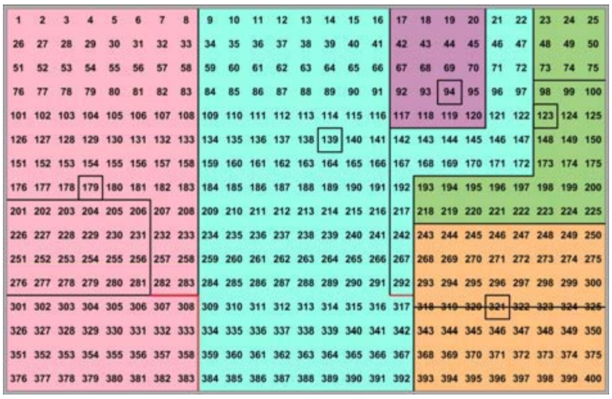

Figure 6: AP locations determined by SA+PS coverage optimization in our Laboratory case study (the coverage regions of each AP are represented in different colors)

Figure 6 presents the coverage-optimized AP locations on our laboratory layout by assuming 5 APs (marked as squared numbers).

The resulting coverage map is presented in Figure 7. We assumed same transmission powers for all APs (5 dBm), same wall attenuations (10 dB) for brick/concrete walls (shown as black solid lines in Fig. 6), and attenuation of 2 dB for gypsum/wood separations (shown as red solid lines). Note that the reception power in each grid point in Figure 7 is determined with respect to AP whose signal suffers the lowest attenuation in the observed point (denoted as the primary AP for that point).

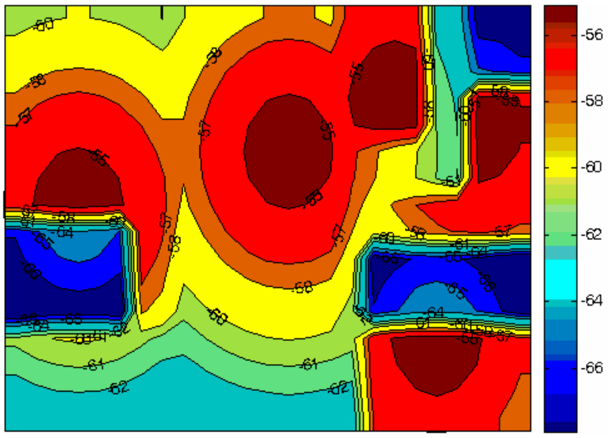

Figure 7: Coverage map after SA+PS coverage optimization in our Laboratory case study (color bar in dBm)

4. INTERFERENCE AND CHANNEL ALLOCATION

Once the access point locations are derived through coverage optimization of the mean reception power, different channels are assigned to the APs. Proper channel allocation is necessary in order to reduce the interference among those WLAN cells that are within the coverage range of each other. The number of available non-interfering channels depends upon the spectral band and the utilized technology, e.g. IEEE 802.11b and 802.11g WLANs support only 3 non-overlapping channels (US Federal Communications Commission allocates 11 operation channels centered between 2.412 and 2.462 GHz with 5 MHz spacing, but the 11 MHz-wide transmit spectrum mask allows for interference-free operation only when operation channels are spaced by four other channels, e.g. channels 1, 6 and 11). Thus, when the total number of APs exceeds three, co-channel interference occurs among neighboring APs and the signal-to-interference ratio (SIR) becomes a relevant parameter that influences the achievable bit rates in the concerned AP cells.

Without proper channel allocation, the co-channel interference can significantly degrade the WLAN performance. Therefore, assuming the APs are placed on their coverage optimized locations, we conduct an additional optimization in order to minimize the influence of the co-channel interference.

We first defined the SIR in each reception point as the ratio of the mean signal power from the primary AP, and the sum of the weighted signal power from all other APs. The weight w_k that is applied to each interference power depends on the spacing k between the primary AP channel m and the interfering AP channel n, so $k = |m - n|$. The weights are calculated according to

$$w_k = \frac{\int_{-f_0+k\Delta f}^{f_0} \mathrm{sinc}[(f - k\Delta f)/f_0]df}{\int_{-f_0}^{f_0} \mathrm{sinc}(f/f_0)df} \tag{5}$$

where $\mathrm{sinc}(x) = \sin(\pi x)/(\pi x)$, $f_0 = 11$ MHz and Δf=5MHz. In (5), $\sin(x)/x$ power spectrum is assumed as according to the IEEE 802.11b standard. Using (5), weights are determined to be: $w_0 = 1$, $w_1 = 0.89$, $w_2 = 0.58$, $w_3 = 0.21$, $w_4 = 0.02$, and $w_k = 0$ for $k \geq 5$.

Similar to (1), the optimal channel allocation is realized by maximizing the objective function given by:

$$OF_{CA} = \frac{1}{M}\sum_{i=1}^{M}(\eta_i - \rho \max(0, \eta_i - \eta_{\max}) - \rho \max(0, \eta_{\min} - \eta_i)) \tag{6}$$

where η_i is the signal to interference ratio in reception point i, η_{max} is the upper bound, η_{min} is the lower bound of the SIR and ρ is the penalty factor. Although the introduction of SIR's upper bound may seem ambiguous at first glance, its appearance in our objective function prevents the occurrence of unnecessary high (or infinity) SIRs in presence of very low interfering power or absence of interference. Very high SIR may lead to inaccurate optimization results. The choice of SIR's lower bound depends on the performance specification of the WLAN client's receivers for sustaining the required bit rates. However, in case of too many APs for given floor layout, part of the service area may be exposed to SIR below its lower bound even after the optimization based on (6). Such an observation may lead to determination of the optimal number of APs for given layout, but is out of the scope of this paper and is left for our future research. In our case study, we set η_{max}=50 dB, η_{min}=10 dB and ρ=10^3.

Figures 8 and 9 depict the SIR maps without and with channel allocation optimization, respectively, for APs placed at the coverage-optimized locations (same locations from Figure 6). The SIR map in Figure 8 is provided for clockwise sequential allocation of the channels to the AP, i.e. channel 1 to AP1 (position 94 on Figure 6), channel 3 to AP2 (position 123 on Figure 6), and etc. Figure 9 displays the SIR map for optimized channel allocation, which is realized by minimizing the objective function OF_{CA} (6) via sequential invocation of the genetic algorithm (GA) and the PS algorithm.

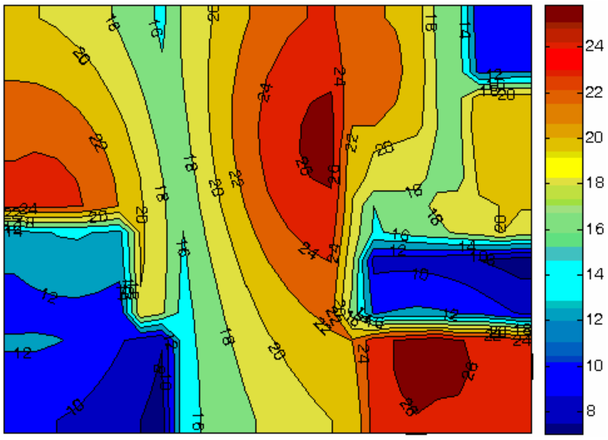

Figure 8: Signal to interference map for manually assigned channels (color-bar in dB)

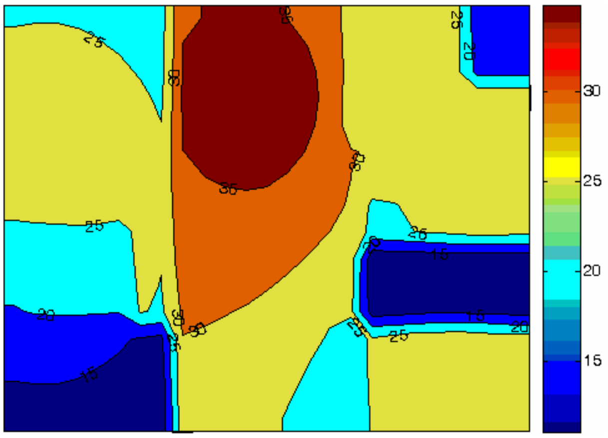

Figure 9: Signal to interference map for optimally assigned channels (color-bar in dB)

The comparison of Figures 8 and 9 clearly demonstrates the benefit of the channel allocation optimization: the unacceptably low SIR in parts of the service area in the former case is brought to acceptable values in the latter case. Such SIR levels sustain the highest achievable bit rates in the entire service area for all commercially available WLAN clients. The average SIR over the entire service area for the manually assigned channels (Figure 8) is 18.8 dB, while the average SIR with optimized channel allocation (Figure 9) is 26.2 dB. The SIR distribution in Figure 9 is restricted between the predefined SIR bounds (10 and 50 dB). The bounds also assisted in obtaining more uniform SIR distribution in entire area (Figure 8 has 10 contour levels as compared to the 5 levels in Figure 9).

5. CONCLUSION

In this paper, we have studied the three relevant network planning issues for large-scale WLAN deployment: propagation modeling, coverage optimization and channel allocation optimization. The dominant path method is utilized to predict the indoor channel's signal reception powers, and is then applied on various deployment scenarios in our laboratory premises. The measurements conducted by our RF site survey tool validated the predicted signal strength values by the dominant path propagation model.

A well-known objective function is utilized for coverage optimization of an arbitrary number of APs in the service area. The sequential invocation of SA and PS algorithms always achieves realistic optimization solutions. On top of the coverage optimization, the channel allocation is realized by the SIR maximization over the entire service area. Our proposed objective function for channel allocation presents clear benefits over the manual (i.e. educated guess) channel allocation.

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