IEEE 802.11s Mesh Network Deployment Concepts

-invited paper-

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***Abstract*— Recent developments in worldwide standardisation bodies [1] show the industry's will to put products enabling mesh-based Wireless Local Area Network (WLAN) on the market. The new technology allows for a transparent extension of the network coverage, without the need of costly and inflexible wires to connect the Access Points (APs).**

Among the envisioned usage scenarios, the provisioning of high-rate wireless Internet access to congested urban areas is one of the most interesting, but also one of the most challenging.

In this paper, we analyse what kind of deployment concepts allow for an efficient setup of a mesh network in such scenarios. To do so, we make use of an realistic system model which incorporates the harsh shadowing in urban areas. Then we present a topology-creating algorithm which positions the APs according to different optimisation criteria in the given area. Based on this algorithm we evaluate different deployment concepts, which incorporate settings for the used frequency band, transmission powers and antenna gains. Finally, the results allow for a substantiated judgement of the capabilities and the involved complexity of WLAN-based mesh networks.

I. INTRODUCTION

The WLAN Standard IEEE 802.11 is successful on the market. One of its main applications is the connection of mobile devices to the Internet: mobile Station (STA) associate to a stationary AP, which routes data packets between the wired and the wireless network. As the distance between an associated STA and its AP is restricted by the propagation loss on the channel, complete coverage of a large environment with wireless access requires several interconnected APs.

If a wired infrastructure is not available to connect the APs with each other, a wireless backbone between multiple APs becomes vital. In this case, APs forward packets from their associated STAs via other APs to the wired network and back. Usually, one AP has more than one neighbouring AP which provides reliability against link failures. Participating APs form a mesh network and are consequently called Mesh Points (MPs). Currently, efforts are ongoing by the Task Group (TG) "S" of IEEE 802.11 to develop an ammendment to the standard which defines the functionality of such an MP, including mechanisms for the path selection, security and enhancements to the Medium Access Control (MAC).

One of the most prominent use cases for the future IEEE 802.11s-based mesh networks are public access networks for dense populated areas. They are comparable to the concept of hotspots, where one or multiple APs are deployed by a provider and connected via a wired backbone. Using a Wireless Mesh Network (WMN) to connect the MPs, installation costs of the wired lines are saved and the network setup becomes more flexible. Changes in the network structure, the topology and the MP density can be implemented to adapt to the fluctuating user behaviour and requirements. Hence, a wireless public access network based on IEEE 802.11s can be seen as a natural enhancement of the hotspot concept.

The paper at hand concentrates on the topology of such IEEE 802.11s-based mesh networks. Under the assumptions of a realistic channel model (introduced in Section II, we present an algorithm that computes an optimised placement of the MPs in a given area (Section III). Furthermore, the requirements on the MP density under a minimum coverage level are analysed. Finally, in Section IV, the comparison of different possible deployment concepts, including intelligent antennas, increased transmission power and different receiver characteristics reveals optimisation strategies.

A. Related Work

The problem discussed in this paper is related to two research areas: The planning of (usually cellular) wireless access networks and the design of WMNs.

Research on the first topic exists since the first deployment of cellular networks, many sophisticated methods exist to tune the system parameters given different optimisation criteria. A broad overview of design parameters for several cellular network types is given in [2]. The hardness of the base station positioning problem for cellular networks was recently shown to be NP-hard in [3]. Hence, approximation techniques are applied, with simulated annealing as the most successful candidate (e. g. [4]).

Although the problems discussed and solved for wireless access networks are similar to the deployment problems in WMNs, the solutions cannot be transfered directly: While overlapping coverage areas should be avoided in a cellular system, they are essential in a mesh network.

In contrast to cellular networks, research on the design of WMNs is much younger; a broad overview of the current state of the art is given in [5]. The problem of the base station positioning is considered in [6]. First, they prove (in a similar way as [3]) the NP-hardness of the problem; then, they propose and analyse an exact algorithm for regular grid topologies. Furthermore, a simple greedy and a local search algorithm is evaluated in random topologies, both with good results. Besides the simpler channel model, the major difference to our work is the restriction of candidate positions for base stations to sites where a STA is placed.

To the best knowledge of the authors, there is no existing work which goes beyond the base station positioning problem and compares different possible deployment concepts of WMNs. We fill this gap and provide a guide which setup-dependant parameter settings allow for a cost-efficient and successful deployment of IEEE 802.11-based WMNs.

II. System Model

We consider a circular area A with radius $r = 250\,\mathrm{m}$ which shall be covered with wireless Internet access, using a mesh network consisting of n MPs positioned at p_i, $i = 1 \ldots n$. Each MP covers a fraction of A, denoted as COV_i, which is determined by the system model. We divide this model into two parts: the channel and the capability of the physical layer.

A. Channel Submodel

The channel submodel determines the received signal quality of a transmission from node N_i to N_j, positioned at p_i and p_j, respectively. One of the most important requirements for this model is the inclusion of the severe shadowing which results from the combination of non line of sight conditions and the used spectrum, which is well above the 2 GHz band, i. e. 5.5/2.4 GHz for IEEE 802.11a/g. This implies that not only the distance between the two nodes needs to be incorporated.

Consequently, in this model two elements attenuate the received signal: A deterministic path loss pl and a stochastic shadowing s. For the path loss, the formula from [7] is applied to compute the path loss between the two nodes:

$$\begin{aligned} \mathrm{pl}(p_i, p_j)\,[\mathrm{dB}] =& 10\gamma \log_{10}\left(d(p_i, p_j)\right) \\ &+ 20 \cdot \log_{10}\left(\frac{c}{f_c \cdot 4\pi}\right), \end{aligned} \tag{1}$$

where

γ stands for the path loss factor,
$d(p_i, p_j)$ is the distance between p_i and p_j,
c denotes the speed of light and
f_c is the centre frequency.

Signal measurements in urban areas show that the shadowing fluctuation can be characterised by a log-normal distribution [8], where the signal levels (measured in dBm) follow a Gaussian distribution. Furthermore, [9] highlights that spatial correlation properties of the random process play a significant role.

Hence, we follow the discussion in [10] [11] and generate a 4-D Normal process that depends on the location of the transmitter and the receiver. One instance of this process is represented by the 4-D shadowing map $\mathrm{s}(x_i, y_i, x_j, y_j)$.

The correlation between the values ensures that a minor movement of the transmitter or the receiver does not result in a major change of the shadowing. As each movement has an independent and equal effect on the correlation [11], the correlation function can be described by the product of two independent identical 1-D Autocorrelation Functions (ACFs). This ACF can be modelled using an exponential decay function [12]:

Table I: Channel model parameter values for dense urban scenarios

γ	3.5	Path loss factor
σ_{shadow}	8	Shadow variance
d_{cor}	50 m	Decorrelation distance

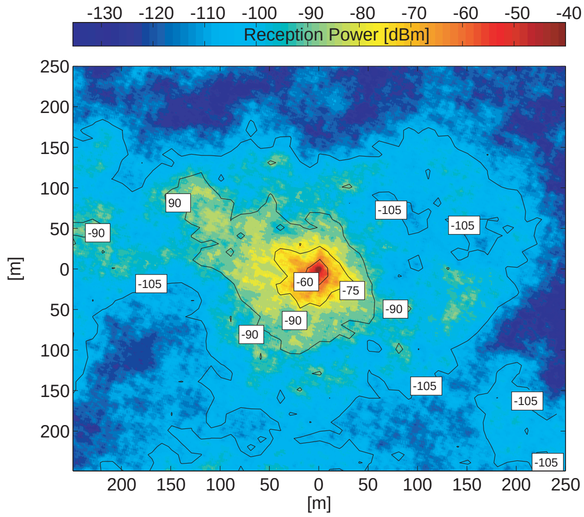


Figure 1: Reception power (in dBm) from a sender positioned at the centre and transmitting with 23dBm.

$$R\left(\Delta d\right) = e^{\frac{-|\Delta d|}{d_{cor}} \ln 2}. \tag{2}$$

The parameter d_{cor} corresponds to the distance at which the correlation drops to 50%.

In order to simulate the shadowing process, we apply the sum-of-sinusoids method where $\mathrm{s}(.)$ is approximated by

$$\hat{\mathrm{s}}(x_i, y_i, x_j, y_j) = \sum_{n=1}^{N} c_n \cos\left(2\pi f_n (x_i, y_i, x_j, y_j)^T + \theta_n\right). \tag{3}$$

The correct setting of the parameters N, c_n, f_n and θ_n depends on the Joint Correlation Function (JCF) and is explained in [11].

For the dense urban scenarios under consideration, recommended model parameter values can be seen in Table I. Together with optional antenna gains g_i and g_j at the transmitter and the receiver, the received signal strength during a transmission with transmission power P_i dBm can be computed as

$$\begin{aligned} \mathrm{P}\left(p_i, p_j\right)[\mathrm{dBm}] =& \mathrm{P}_i\,[\mathrm{dBm}] + g_i + g_j \\ &- \mathrm{pl}(p_i, p_j) - \mathrm{s}(p_i, p_j) \end{aligned} \tag{4}$$

Using this model, a node positioned at $(0, 0)$ and transmitting with 23 dBm at 5.5 GHz, could for example produce a reception footprint as plotted in Figure 1.

Table II: Minimum Received Signal Strength ($\mathrm{RSS_{min}}$) for the IEEE 802.11a/g Modulation & Coding Schemes (MCSs).

MCS	PHY rate	$\mathrm{RSS_{min}}$ (dBm) 802.11 standard	Cisco Aironet 1240AG [14]
BPSK 1/2	6 Mb/s	-82 dBm	-91 dBm
BPSK 3/4	9 Mb/s	-81 dBm	-85 dBm
QPSK 1/2	12 Mb/s	-79 dBm	-83 dBm
QPSK 3/4	18 Mb/s	-77 dBm	-81 dBm
16-QAM 1/2	24 Mb/s	-74 dBm	-78 dBm
16-QAM 3/4	36 Mb/s	-70 dBm	-74 dBm
64-QAM 2/3	48 Mb/s	-66 dBm	-73 dBm
64-QAM 3/4	54 Mb/s	-65 dBm	-73 dBm

As it can be seen in this example, the node's transmission area is frayed and non-contiguous, which is a result of the shadowing. Hence, a static transmission range cannot be defined. Furthermore, link symmetry cannot be assumed, as $\mathrm{s}(p_i, p_j) = \mathrm{s}(p_j, p_i)$ holds only seldom for distances around and larger than d_{cor}. As a consequence, it is impossible to cover the area using a geometrical pattern, e. g. hexagonal cells, and to assume a regular placement of the MPs.

B. Physical Layer Submodel

The physical layer submodel decides under which conditions the transmitted packet is decoded error-free at the receiver. As the goal of the system model is to compute the coverage area of each MP_i (A_i), we assume optimal, i. e. interference free conditions. Hence, the reception probability depends on the received signal strength and the quality of the receiver radio only.

IEEE 802.11a/g defines the minimum Received Signal Strength (RSS) of a standard compliant device [13]: If the stated RSS is reached, the receiver's Packet Error Rate (PER) shall be less than 10% at a packet length of 1000 B. Hence, these values provide the minimum capability that can be expected from a commercially available radio.

Existing hardware aims to perform better than the values given in the standard; hence, lower input sensitivities can be assumed. Some vendors publish performance sheets of the used radio which gives a good impression the capabilities of current available devices.

In Table II, the minimum RSSs for the Modulation- and Coding Schemes (MCSs) of IEEE 802.11a/g are given, both as required by the standard as well as for an exemplary up-to-date AP, the Cisco Aironet 1240AG.

Using these values, it is possible to define the coverage area COV_i for an MP positioned at p_i. First, the *uplink* and *downlink* coverage areas are defined:

$$\mathrm{COV}_{i,\leftarrow}(\mathrm{MCS}) = \quad \{p \in A : P(p, p_i) \geq \mathrm{RSS_{min}}(\mathrm{MCS})\} \tag{5}$$

$$\mathrm{COV}_{i,\rightarrow}(\mathrm{MCS}) = \quad \{p \in A : P(p_i, p) \geq \mathrm{RSS_{min}}(\mathrm{MCS})\} \tag{6}$$

Finally, the *bidirectional* coverage area COV_i is the intersection of $\mathrm{COV}_{i,\leftarrow}$ and $\mathrm{COV}_{i,\rightarrow}$.

III. Mesh Network Topologies

With the prerequisites from the system model described in Section II we can define useful mesh network topologies for a wireless public access network based on IEEE 802.11s.

The area A is called to be *fully covered* if MPs are positioned in it such that the union of their bidirectional coverage areas is equal to to the area itself. With our model, this amount of coverage requires many MPs to fill all small coverage holes. Hence, we follow a more practical approach: The area is covered with a grid using a spacing of a. This grid defines *measurement points* at each intersection. If at least b percent of these measurement points belong to the union of the MPs coverage areas, A is said to be covered.

For the circle A with radius $r = 250\,\mathrm{m}$, we set the grid spacing to $a = 15\,\mathrm{m}$ and the percentage $b = 95\%$. Hence, 870 measurement points are defined and 827 of those have to have a RSS of at least $\mathrm{RSS_{min}}$.

While it is easy to find a placement of MPs with the required coverage, the optimisation problem to find a placement with a minimum number of MPs is NP-hard [3]. Therefore, we design a greedy positioning algorithm, printed as Algorithm 1, which takes into account the harsh shadowing conditions during the placement.

The algorithm works in an iterative manner: Starting from the centre, circles with increasing radii are examined for possible placements. If a coordinate is found where an MP i) enlarges the current coverage and ii) is connected to at least one other MP, it is added to the set of MPs. In the pseudo-code, the first while-loop (lines 7 to 24) increases stepwise the maximum distance from the centre which a new MP is allowed to have. The second loop (lines 8 to 21) then places new MPs so that the coverage is enlarged over the new circle. This is done by working on the list "PermittedPositions": It holds all measurement points inside the circle where a new placed MP

- would be connected to the existing mesh network, i. e. has a RSS more than MPMinRSS and
- does not exhibit too much signal from other MPs by having a RSS less than MPMaxRSS.

The list is updated in line 18 and 23 when a new MP is placed or the radius of the circle is enlarged, respectively. Furthermore, this list is sorted by the descending distance to the nearest already placed MP.

The definition of the list plus the sorting define a heuristic how to search the available positions. It shall guarantee that the first measurement point in it has a good potential to extend the coverage of the existing network. Due to the harsh shadowing, this assumption needs to be tested before the MP is really added. This is done in line 14: The previous computed coverage area of the candidate position, COV_p is compared with the coverage area of the network, COV_{all}. If at least the fraction $thes_{cov}$ of COV_p was previously uncovered, the MP is added. Hence, the placement is greedy (as the list is not searched completely), but must reach a minimum usefulness. A straight-forward enhancement of the algorithm starts with

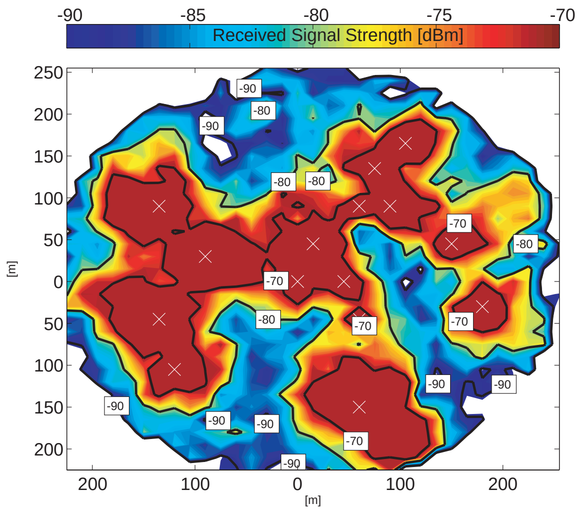


Figure 2: An example for a complete mesh network with a 95% coverage of the given area. Crosses represent one of the 14 MPs, the colour indicates the maximum RSS in dBm

a large value of $thes_{cov}$ and adapts it during the runtime, allowing less optimal placements to fill out coverage holes.

The algorithm stops when the complete area has been searched for possible placements (beside a small border) and if either the coverage b is reached or if no further positions can be found.

For the following results, we parameterise the algorithm by setting

- the size of the border to 30 m,
- the minimum coverage addition $thres_{cov}$ to 50% of the newly placed MP's coverage,
- MPMinRSS to $\text{RSS}_{\text{min}}(\text{QPSK}1/2)$ and
- MPMaxRSS to $\text{RSS}_{\text{min}}(\text{64-QAM}2/3)$

An exemplary result of the algorithm can be found in Figure 2. It displays the positions of 14 MPs in the area A. Additionally, Figure 2 indicates the maximum RSS which can be received by a mobile station from the MPs which is related to the maximum transmission rate.

IV. Deployment Concepts

Using the Algorithm 1 described in the previous section, it becomes possible to discuss different deployment concepts for mesh networks. Essentially, these concepts describe how different degrees of freedom can be exploited during the planning and the setup of the network. In the case of IEEE 802.11s based mesh networks, there are many possible parameters which can be used to fine-tune the network. We restrict the analysis on the following factors:

- Two different frequency bands are currently available to operate IEEE 802.11 outdoors. In Europe, they are located at 2.4 to 2.485 GHz with 3 non-overlapping channels, and from 5.47 to 5.725 GHz with 11 non-overlapping channels. While the lower band provides

Algorithm 1 MP-Placement

MPs $\leftarrow \emptyset$
ToBeCovered $\leftarrow$ Set of all measurement points
$\text{COV}_{all} \leftarrow \emptyset$
$\text{RSSMap}_{all} \leftarrow$ Matrix with $-\infty$ for all measurement points
PermittedPositions $\leftarrow$ Centre
MaxDistToCentre $\leftarrow$ 0
% Iterate over circles with increasing radius
while (MaxDistToCentre < Radius - Border) **do**
  % Add MPs while further positions can be found AND the area is not covered
  while ($|\text{PermittedPositions}| > 0$) AND ($|\,\text{COV}_{all}\,| < |\text{ToBeCovered}| \cdot b$) **do**
    % The array is sorted by distance, so the first candidate has the maximum possible distance to the MPs
    $p \leftarrow$ shift(PermittedPositions)
    % Compute the bidirectional coverage for p
    $\text{RSSMap}_{p,\rightarrow} \leftarrow \text{P}(p, \text{ToBeCovered})$
    $\text{RSSMap}_{p,\leftarrow} \leftarrow \text{P}(\text{ToBeCovered}, p)$
    $\text{RSSMap}_{p,\leftrightarrow} \leftarrow \min(\text{RSSMap}_{p,\rightarrow}, \text{RSSMap}_{p,\leftarrow})$
    $\text{COV}_p \leftarrow$ Set of all measurement points where $\text{RSSMap}_{p,\leftrightarrow} > \text{RSS}_{\text{min}}$
    % Check if the candidate increases the coverage
    if ($|\,\text{COV}_p \cap \text{COV}_{all}\,| < |\,\text{COV}_p\,| \cdot thres_{cov}$) **then**
      % Add the MP and update the coverage status
      MPs $\leftarrow$ MPs $\cup\ p$
      $\text{COV}_{all} \leftarrow \text{COV}_{all} \cup \text{COV}_p$
      $\text{RSSMap}_{all} \leftarrow \max(\text{RSSMap}_{all}, \text{RSSMap}_{p,\leftrightarrow})$
      % Update the permitted positions
      PermittedPositions $\leftarrow$ All measurement points from RSSMap_{all} with
        RSS $>$ MPMinRSS
        RSS $<$ MPMaxRSS
        Distance to centre $<$ MaxDistToCentre
      Sort PermittedPositions by Distance to nearest MP
    end if
  end while
  Increase MaxDistToCentre by $2.5\cdot$ Border
  PermittedPostitions $\leftarrow$ All new measurement points which match the three conditions from above
end while

better propagation characteristics, in the upper band less interference can be expected from existing devices.
In the analysis, the centre frequencies 5.5 and 2.4 GHz are considered.

- The increase of the maximum transmission power enlarges directly the coverage area of the MP. Of course, this is bounded by regulations (e. g. to 20 dBm for the low band and 30 dBm for the high band in Europe). Furthermore, increasing the transmission power increases also the interference that is imposed on other MPs.
In the analysis, we examine the complete range from 17 to 30 dBm for both frequency bands.
- As the MPs are stationary, it becomes advantageous to use intelligent receive antennas which rise the antenna gain for MP to MP links. For the network performance this antenna gain is vital: It extends the coverage area of each MP in a specific, very narrow sector. Hence, it increases the capacity of the mesh backbone (which has to carry the cumulative traffic from all STAs). Furthermore, fewer MPs are needed to cover the area as the overlap of two MPs can be decreased.
The analysis incorporates that each MP has 3 directed antennas with antenna gain ranging from 0 to 20 dB.
- As it was shown in Table II, the minimum RSS which is required to decode a signal varies with different hardware. In the worst case, the hardware fulfils only the minimum requirements, which lowers the coverage area of an MP. If better hardware can be assumed, the coverage is provided also at larger distances.
To demonstrate the effect of both assumptions, we consider -82 and -91 dBm for the minimum RSS of the MCS BPSK $1/2$.

In summary, a deployment concept can be described as a fourtuple:

$$dc \in \{2.4; 5.5\} \times [17 \ldots 30] \times [0 \ldots 20] \times \{-82; -91\} \quad (7)$$

In the following, the influence of the parameters on the mesh network topology is evaluated. In a first step, we assess the average number of MPs which are required for a 95% coverage. If a lot of MPs are needed, it has direct implications on the feasibility of the deployment: Not only does it become more expensive to aquire the deployment sites, the larger network size induces also more coordination overhead, leading to a reduced system capacity.

Second, we assume that the number of MPs is restricted in advance and evaluate the impact of the used parameters on the resulting coverage.

A. Mesh Point Density

As throughout the paper, we are considering a circular area with radius 250 m in which 870 measurement points are placed on a grid with 15 m distance. The MP-placement algorithm is fed with the deployment concept values, the grid data and an instance of the shadowing process and positions the MPs until at least 95% coverage is reached. This is repeated with different random values for the shadowing, until the mean value becomes stable, i. e. the size of the 95%-confidence interval of the mean is below 10%.

Figure 3 shows the resulting mean number of required MPs for all deployment scenarios; each subfigure corresponds to one frequency band and one $\mathrm{RSS}_{\min}$.

It can be seen that the number of MPs varies significantly among the different deployment concepts, from less than 10 up to 60 and more. Generally, the increased path loss in the 5.5 GHz band (Figures 3a and 3b) leads to many MPs, especially for low transmission power. This discards these parameter combinations for practical usage. Hence, the permitted maximum transmission power of 30 dBm has to be exhausted for actual installations, leading to an average of about 15 MPs for the given area A. The resulting high interference level requires intelligent Transmit Power Control (TPC) algorithms, which lower the used power if possible.

At a first glance, the deployment concepts using the 2.4 GHz band (Figures 3c and 3d) require much less MPs to cover area A. Taking into account that the maximum transmission power is limited to 20 dBm in Europe, this conclusion cannot be sustained. Under this limitation, the required number of MPs is around 20. Combined with the higher interference level from the plenty of devices that are in use in this favoured band and the lower number of channels, this deployment concept becomes less attractive. In the US, where approximately 4 dB more transmission power is permitted, the 2.4 GHz has a small advantage.

While the discussed parameters have a strong influence on the number of required MPs, an adjustment of the antenna gain or the $\mathrm{RSS}_{\min}$ has a lower impact on this number. This allows us to restrict the network planning to deployment concepts with low $\mathrm{RSS}_{\min}$ and small antenna gains. If the hardware requires a higher $\mathrm{RSS}_{\min}$, it has only minor impact on the performance as the MPs are positioned dense enough to provide the 95% coverage.

For the antenna gain this strategy has major advantages in practice: In the initial setup of the network, no cost-intensive intelligent antennas have to be used. If later the number of users rises and the network capacity has to be enlarged, an change to better antennas can be done instead of installing new MPs.

B. Coverage with limited number of Mesh Points

In the previous section, the minimum coverage requirement was fixed at 95% and the number of MPs was evaluated. This provides a conclusion which deployment concepts require a reasonable number of MPs to cover the given area.

In this section, we formulate the question the other way around: Assuming n MPs are available to build up the mesh network, which coverage can be achieved? As this question introduces a new variable, we restrict our view to the subset of deployment concepts which use the 5.5 GHz band and -82 dBm $\mathrm{RSS}_{\min}$.

Figure 4 presents the mean coverage levels which can be achieved with 5, 10, 15 and 20 MPs. It can be seen that it

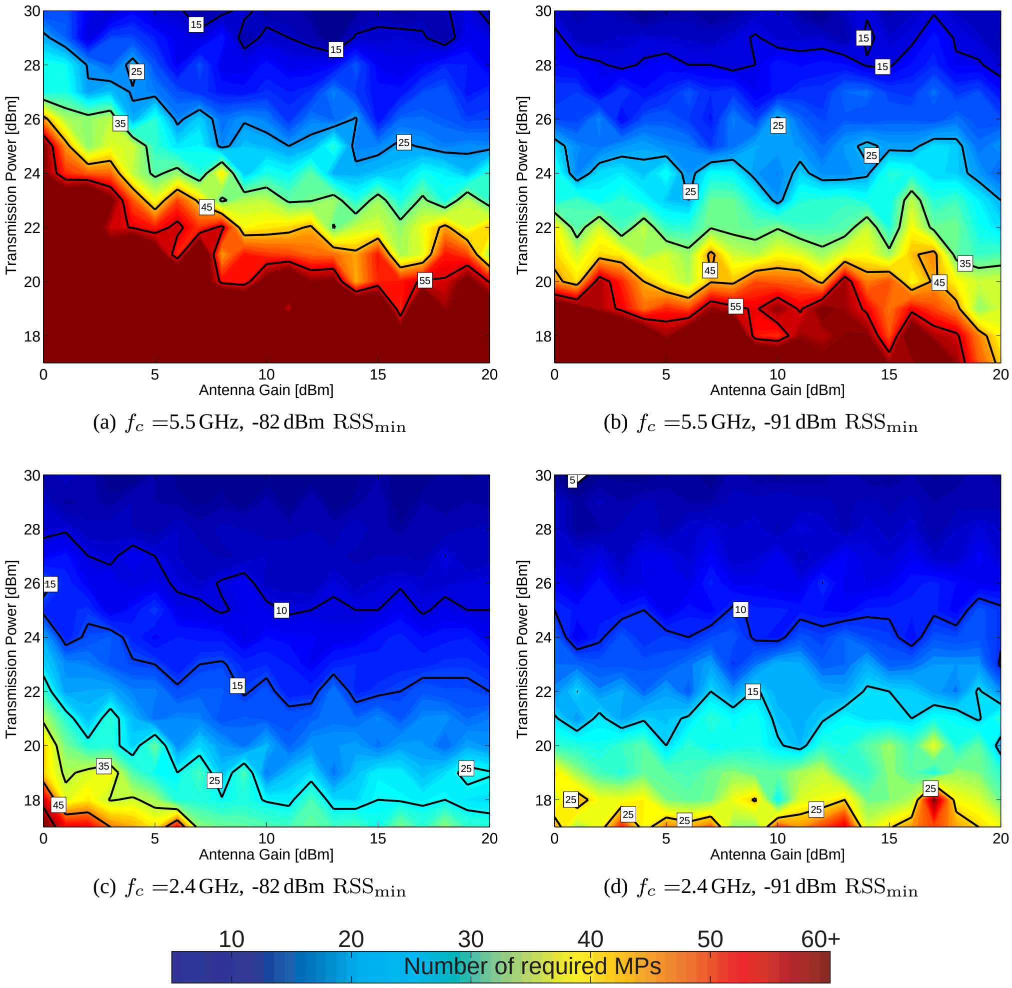


Figure 3: Average number of MPs which are placed by Algorithm 1, depending on the used deployment concept.

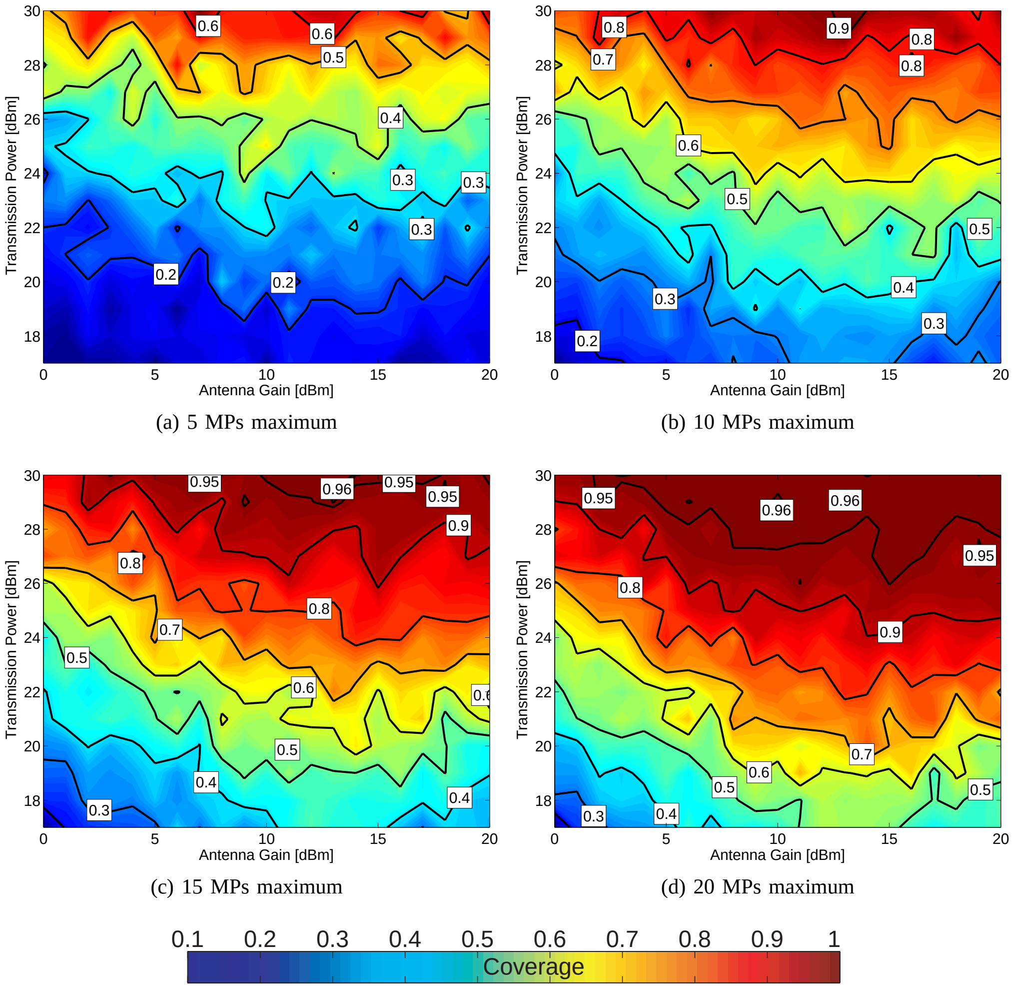
is not possible to reach a coverage of more than 60% using 5 MPs (Figure 4a). But already the deployment of 10 MPs (Figure 4b) is able to reach 90% with the right combination of parameters, i. e. exploiting the maximum transmission power of 30 dBm and an antenna gain of 12 dBm. With more than 10 MPs, a coverage of more than 90% can be reached, a result which was already concluded in Section IV-A.

In contrast to the previous section, the antenna gain has a larger influence on the results, especially if 15 or more MPs are deployed: If the transmission power is reduced, the decrease of the coverage can be partly compensated with an increased antenna gain. As an example, in the 20 MPs case, the deployment concept with a transmission power of 26 dBm and an antenna gain of zero provides the same coverage as a power of 20 dBm and a gain of 14 dB. This is a result of the strategy followed by the placement algorithm: As the mesh network has to be connected, the coverage area of one MP has to include at least one other MP if the antenna gain is zero. This implies a large overlap of the two areas. If antenna gain can be exploited, this overlap can be decreased, which allows the same number of MPs to cover a larger area.

V. Conclusion

This paper presents and evaluates solutions for two interrelated problems: First, the MP placement to generate optimised topologies for IEEE 802.11s mesh networks. This problem is aggravated by the realistic channel model, which simulates the shadowing using a 4-D spatial correlated log-Normal process. We have developed a greedy algorithm that approximates an optimal positioning, which is able to generate feasible topologies.

Second, possible deployment concepts for IEEE 802.11s-based mesh networks are introduced. They describe the decisions that need to be addressed during the planning process of the network, including the used frequency band, the minimum receiver sensitivity, the maximum transmission power and the antenna gain. Using the MP placement algorithm, we have shown that the right choice of parameters allows for a mesh network with low number of MPs to cover the given area. Furthermore, the analysis provides insights to the relation between the number of MPs and the reached coverage. Hence, a cost-efficient deployment which is suited to the system requirements is possible.



(a) 5 MPs maximum (b) 10 MPs maximum (c) 15 MPs maximum (d) 20 MPs maximum

Figure 4: Mean achieved coverage levels with 5, 10, 15 and 20 MPs. For all subfigures, f_c =5.5 GHz, -82 dBm $\mathrm{RSS}_{\mathrm{min}}$ is used.

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REFERENCES

[1] “Draft Amendment to Standard for Information Technology - Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: Amendment: Ess mesh networking,” June 2006.

[2] A. R. Mishra, *Fundamentals of Cellular Network Planning and Optimisation: 2G/2.5G/3G... Evolution to 4G*. John Wiley and Sons, May 2004.

[3] C. Glasser, S. Reith, and H. Vollmer, “The complexity of base station positioning in cellular networks,” *Discrete Applied Mathematics*, vol. 148, no. 1, pp. 1–12, 2005.

[4] R. Mathar and T. Niessen, “Optimum positioning of base stations for cellular radio networks,” *Wireless Networks*, vol. 6, pp. 421–428, Dec. 2000.

[5] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: a survey,” *Computer Networks*, vol. 47, pp. 445–487, Mar. 2005.

[6] A. Bogdanov, E. Maneva, and S. Riesenfeld, “Power-aware base station positioning for sensor networks,” in *Proc. of INFOCOM 2004*, (Hong Kong, PRC), p. 11, Mar. 2004.

[7] B. Walke, *Mobile Radio Networks*. Chichester, Sussex, U.K.: Wiley & Sons Ltd., 1. ed., 1999.

[8] W. C. Y. Lee, *Mobile Communications Engeneering*. New York: McGraw Hill, 1982.

[9] N. Patwari, Y. Wang, and R. J. O’Dea, “The importance of the multipoint-to-multipoint indoor radio channel in ad hoc networks,” in *Proceedings of IEEE Wireless Communication and Networking Conference*, (Orlando, USA), Mar. 2002.

[10] X. Cai and G. B. Giannakis, “A two-dimensional channel simulation model for shadowing processes,” *IEEE Transactions on Vehicular Technology*, vol. 52, pp. 1558–1567, Nov. 2003.

[11] Z. Wang, E. K. Tameh, and A. R. Nix, “A sum-of-sinusoids based simulation model for the joint shadowing process in urban peer-to-peer radio channels,” in *Proceedings of IEEE 62nd Vehicular Technology Conference, 2005 (VTC 2005-Fall)*, (Dallas, USA), p. 5, Sept. 2005.

[12] A. Gehring, M. Steinbauer, I. Gaspard, and M. Grigat, “Empirical channel stationarity in urban environments,” in *Proceedingns if European Personal Mobile Communication Conference*, Feb. 2001.

[13] T. L. Cole and S. J. Kerry, “IEEE Wireless LAN Edition - A compilation based on IEEE Std 802.11-1999 (R2003) and its amendments,” 2003.

[14] “Cisco aironet 1240ag series 802.11a/b/g access point data sheet.” `http://www.cisco.com/en/US/products/ps6521/products_data_sheet0900aecd8%031c844.html`.