An IEEE 802.11 Model for the Planning of Wireless Mesh Networks

Sebastian Max, Yunpeng Zang
Department of Communication Networks (ComNets)
Faculty 6, RWTH Aachen University
52074 Aachen, Germany
Email: smx|zyp@comnets.rwth-aachen.de

Yuan Zhou*, Huimin Zhang
Huawei Industrial Base
Bantian Longgang Shenzhen China
Email: michael|amyzhang@huawei.com

***Abstract*—Service-area specific optimization is a necessity for large-scale wireless networks. For this task, a model to estimate the quality of a radio network configuration is required. In the case of cellular radio networks, much work exists on models for Radio Network Planning (RNP).**

This work cannot be applied to optimize IEEE 802.11-based Wireless Mesh Networks (WMNs), as their multi-hop structure and the distributed medium access deviates significantly from cellular networks. In this paper, we present a model for IEEE 802.11-based WMNs that fulfills the following criteria: (i) It has low complexity, enabling iterative optimization; (ii) it has sufficient accuracy in comparison to simulation; (iii) it includes a physical layer model that takes into account interference and multiple transmission rates.

I. Introduction

IEEE 802.11 for Wireless Local Area Networks (WLANs) was initially designed for small unmanaged networks, consisting of one Access Point (AP) and several Stations (STAs). Recently, IEEE 802.11 is used to provide wireless Internet access to larger areas, e. g. city centers. As the service area of one AP is limited, multiple APs are deployed. To reduce the costs of the wired backbone between the APs, wires are replaced by radio, introducing the Wireless Mesh Network (WMN). In a WMN, Mesh Points (MPs) serve to forward data to or from the nearby AP multi-hop from or to a STA.

Intelligent network deployment is a must to operate a large-scale WMNs. As WMNs are static it becomes possible to plan the topology in advance, taking into account the requirements of the provider, the users, and the service area. This process is denoted Radio Network Planning (RNP).

Due to their multi-hop structure and the characteristics of IEEE 802.11, radio network planning approaches known from cellular networks (e. g. [1]) cannot be applied directly to WMNs. One major difficulty is the quality estimation of a network configuration, as realistic saturation throughput estimation is non-trivial. To be useful as a part of an optimization procedure, this estimation should have high accuracy. Furthermore, as many iterations may be needed to find an adequate configuration, a low runtime complexity is required.

The paper at hand describes and evaluates a model for the quality estimation that fulfils these requirements. Before that, we overview in Section II different existing models for WMN and discuss their applicability in the RNP process. Then, Section III introduces the developed model. Based on simplifying assumptions, it allows for a computation of the saturation throughput for a given network. We compare in Section IV the model with event-driven simulation. We find that the developed model exhibits a mean accuracy above 85% in comparison to simulation using only 3% of the runtime.

*Corresponding Author

II. Related Work

A. IEEE 802.11 MAC Models

Markov-Chains are a prominent tool to convert the dynamics of the IEEE 802.11 Medium Access Control (MAC) into a static model. By deriving state probabilities, the interaction between the participating nodes and thus successful and failed packet transmissions can be predicted. Based on the seminal work from Bianchi [2], recent extensions allow for the modeling of non-saturated sources [4] or different traffic categories [5]. All models based on this approach share the assumption that packet errors result only from identical backoff values and thus frame “collisions” at the receivers. While this model is applicable in small WLANs where all nodes are in mutual reception range, it does not capture the challenges of wireless transmissions in WMNs.

Hidden nodes and multiple Modulation- and Coding Schemes (MCSs) require to model each link differently, depending on its position and its neighbors. Therefore, the model’s complexity becomes similar to an event-based simulation.

B. Wireless Network Models

A different approach is taken by the work presented in [6] and its extensions (e. g. [7] for hybrid wired/wireless networks). Here, the authors derive upper capacity bounds for the network, depending on the maximum link throughput and the network size. In contrast to the work described in the preceding section, the used models for transmission errors (especially the Signal to Interference plus Noise Ratio (SINR)-based “Physical Model”) are able include the mentioned characteristics of the wireless channel.

While the upper bounds hold for the saturation throughput in IEEE 802.11-based networks, they are not intended as a sharp limit for them. In contrast, it has been shown that the performance of the IEEE 802.11 MAC is considerable lower and scales differently with the network size [8].

C. Combined Models

Recent contributions show efforts to combine the effects of the IEEE 802.11 MAC with realistic wireless channels and frame error models.

One approach is to define for each link an “interference range”, containing all nodes that potentially interfere with the transmission. This approach enables introducing interference into a Markov-chain MAC model [9]. However, interference is underestimated: Two interference sources that are harmless must be outside the interference range. Hence, a simultaneous transmission must be also harmless, although the combined interference leads to transmission errors.

Recent work successfully combines the Markov-Chain model from [2] with a SINR-based frame error model [10], [11]. Their work is most related to ours, as it combines certain aspects from both Physical Layer (PHY) and MAC of IEEE 802.11, while giving up details for low complexity. Nevertheless, they consider only one MCS per link, which is in contrast to the eight available MCS of IEEE 802.11a/g (or the more than 100 in the current draft of IEEE 802.11n); this simplification can only be used in networks without Rate Adaptation (RA) and leads to an underestimation otherwise.

D. Our Contributions

In this paper, we go beyond the existing work in three ways. First, we allow for a set of MCSs with different susceptibility to interference; the selection of the MCS by the transmitter is encapsulated in a RA model. Hence, the multi-rate ability of IEEE 802.11a/g can be included appropriately. Second, the model covers not only single-hop networks, but is applicable to any multi-hop network with static topology. Third, in addition to the saturation throughput our model is able to estimate the *occupancy* of any node in the network. Therefore, it becomes straightforward to identify the bottleneck of a network, enabling a precise RNP optimization process.

III. STATIC IEEE 802.11 MODEL FOR WMNS

The major challenge for a WMN model is the complex interactions between links. One important property is the *effective rate* $r(i,j)$ of a link i to j, defined as the mean number of data bits that i is able to transmit successfully to j per second. First, this rate depends on the MCS selected by i and the overhead from the channel access procedure. Second, $r(i,j)$ depends on the Packet Error Rate (PER) and thus the interference from surrounding nodes. If packet errors occur frequently, i selects a more robust MCS. Therefore, it has to transmit longer for the same amount of data, possibly increasing interference to other nodes. These, in turn, may also change their MCS, which effects the interference at j, etc.

As a second important property is the *channel busy fraction* $p_{busy}(i)$ of a node i, defined as the fraction of time the node detects the channel as occupied by other transmissions.

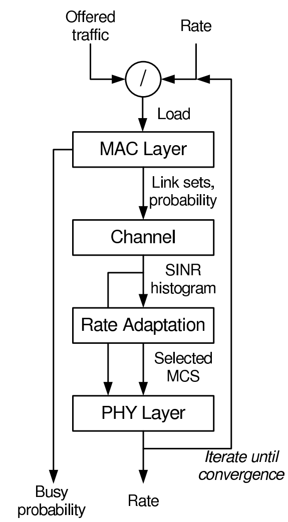


Fig. 1: Core part of the static IEEE 802.11 MAC model

As defined by the IEEE 802.11 protocol, nodes refrain from transmitting during this time. Similar to the effective rate, this fraction depends on the neighboring nodes.

The major part of the model is dedicated to these dependencies between the links. Figure 1 shows how an iterative process is used to approximate the effective rate $r(i,j)$ between nodes i and j; in each iteration, the steps are carried out for all links (i,j), $1 \leq i,j \leq n$:

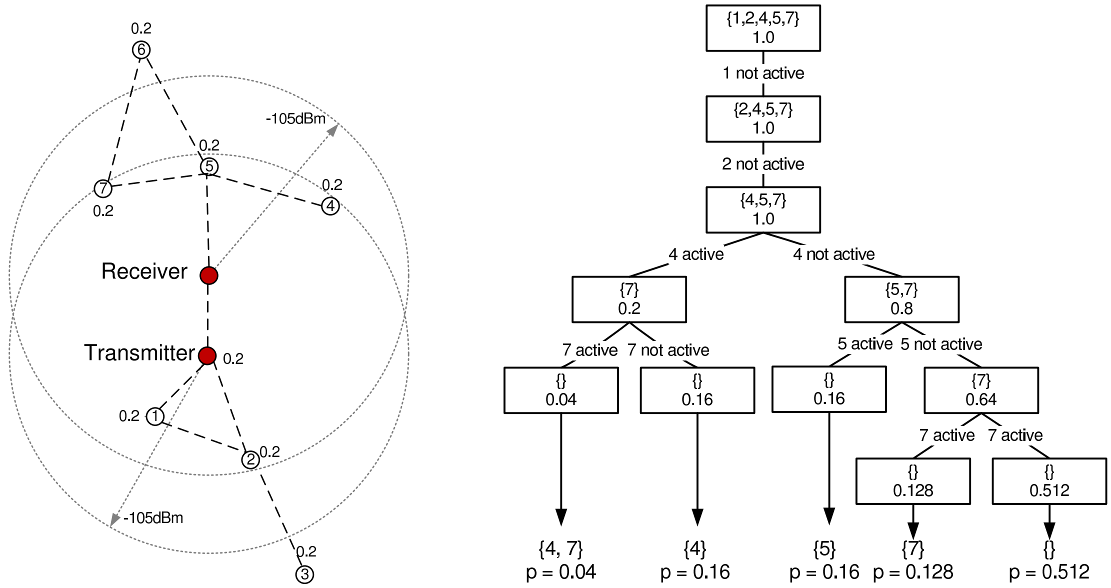
1) The offered link traffic $o(i,j)$ divided by the link rate $r(i,j)$ gives the load $l(i,j)$ for the link from i to j.
2) The MAC layer model in Section III-A uses the loads of all links to calculate probabilities for simultaneous transmissions that result either in interference or in a busy channel.
3) The probabilities for simultaneous transmissions are converted into a SINR histogram, based on the channel model in Section III-B.
4) The SINR histogram determines the selected MCS, using a RA model explained in Section III-C.
5) The PHY model from Section III-D combines the SINR distribution and the selected MCS to the new link rate $r(i,j)$, which is used in the next iteration step.

The iteration converges if the maximum change in $r(i,j)$ for all links is small, i. e. 1% in our implementation.

In the following, the parts of the model are presented in depth. Then, in Section III-E this iterative procedure is used to compute the saturation throughput.

A. Medium Access Control

A central element in the Distributed Coordination Function (DCF), defined by the IEEE 802.11 MAC, are the Clear Channel Assessment (CCA) methods that determine the channel condition: First, the Physical Clear Channel Assessment (P-CCA) relies solely on the received signal energy; if this exceeds a threshold, the channel is seen as busy. Second, Virtual Clear Channel Assessment (V-CCA) uses the frame-



(a) Example network for the interferer tree in Figure 2b

(b) Interferer Tree for the link transceiver to receiver in the example network in Figure 2a

Fig. 2: Exemplary network and corresponding interferer tree for one link.

and Network Allocation Vector (NAV)-length transmitted in the PHY and MAC header which indicate the length of the current frame and the current frame exchange, respectively. If a node overhears this information, it defers from the channel access for the indicated duration.

For any link in the network, the CCA operation controls (i) which sets of nodes are able to transmit simultaneously with this link and (ii) which nodes may block the link by their transmission. The computation of (i) and (ii) together with the corresponding probability is the task of the MAC model. The following explanation of the algorithm (given as Algorithm 1) uses the link "Transmitter $\rightarrow$ Receiver" in the network in Figure 2a as an example. To compute the probabilities, the load of each node must be given; in the example it is indicated as small number next to the node.

In a first step, the nodes which affect the link are stored into the candidate set I_{cand}; they are characterized by having a load of more than zero and being inside a defined distance from either the transmitter or the receiver, which is set to -105 dBm. In the example, $I_{cand} = \{1, 2, 4, 5, 7\}$.

The algorithm proceeds in a depth-first search over I_{cand} to enumerate all sets of nodes which can transmit simultaneously with the selected link, called *interference sets*. The corresponding search tree of the example is given in Figure 2a. In each recursion step a node i is selected from I_{cand}. Depending on the node two cases are distinguished: (i) i cannot transmit simultaneously to the transmitter and adds to its channel busy fraction (Line 6). (ii) i can transmit simultaneously; this creates two children: one for a passive and one for an active i (Lines 10 and 14, respectively). In the case that i is active, the set of candidate interferers is updated to contain only the nodes not blocked by i.

Algorithm 1 Static MAC model: computation of interference sets and blocking probability. Init: $\mathrm{ComputeInterfererSets}\,(tx, I_{cand}, \{\}, 1.0)$

Input: Active transmitter tx, candidate interferers I_{cand}, active interferers I_{active}, probability p

Output: $\mathbb{I} = \{(I, p_I)|I$: Interferer set with probability $p_I\}$, p_{busy}

1: **if** $I_{cand} = \{\}$ **then**
2:     **return** $\{(\{\}, p)\}\,,\quad 0.0$
3: **end if**
4: $i \leftarrow$ one candidate interferer from I_{cand}
5: **if** tx is blocked by transmission from i **then**
6:     $\mathbb{I}, p_{busy} \leftarrow \mathrm{ComputeInterfererSets}\,(tx, I_{cand} - i, I_{active}, p)$
7:     $p_{busy} \leftarrow p_{busy} + p \cdot p_{tx}(i)$
8:     **return** $\mathbb{I},\quad p_{busy}$
9: **end if**
10: $\mathbb{I}^-, p^-_{busy} \leftarrow \mathrm{ComputeInterfererSets}\,(tx, I_{cand} - i, I_{active}, p \cdot (1 - p_{tx}(i)))$
11: **if** $p_{tx}(i) > 0$ **then**
12:     $I^{new}_{active} \leftarrow I_{active} + i$
13:     $I^{new}_{cand} \leftarrow \{j \in I_{cand}|j$ is not blocked by $i\}$
14:     $\mathbb{I}^+, p^+_{busy} \leftarrow \mathrm{ComputeInterfererSets}\,(tx, I^{new}_{cand}, I^{new}_{active}, p \cdot p_{tx}(i))$
15:     Append i to all sets in $\mathbb{I}^+$
16: **end if**
17: **return** $\mathbb{I}^+ \cup \mathbb{I}^-,\quad p^+_{busy} + p^-_{busy}$

A leaf of the tree is found if I_{cand} is empty; it represents one interference set, containing all nodes selected as active on the branch. The probability of the set is calculated as the product probability of each case in the branch, which is determined by the transmission probabilities of the nodes on the path. In the same way, p_{busy} of the transmitter is calculated by summing up the transmission probabilities of the blocking nodes.

B. Wireless Channel

We assume that either on-site measurements or at least a modeling of the specific propagation conditions in the service area have been performed. Therefore, for a given network configuration of n nodes, the average reception power at node j during transmission from node i is known or can be approximated. In the model, we will denote this power as $P(i, j)$.

Using $P(i, j)$, it is straightforward to convert the output of the MAC model (a set $\mathbb{I}$ consisting of tuples (I, p_I), where I is a set of nodes and p_I is the associated probability that these nodes transmit simultaneously, see Section III-A) into an SINR histogram for a specific link i to j. This is done by calculating for each set in $\mathbb{I}$ the corresponding SINR value:

$$\mathrm{SINR}_I = \frac{P(i,j)}{N + \sum_{h \in I} P(h,j)},$$

where N represents background and receiver noise. Then, all SINR_I with weight p_I are sorted into a histogram, approximating the SINR distribution of this link.

C. Rate Adaptation (RA)

RA in wireless networks deals with the problem that the transmitter has to select the MCS for a transmission using limited knowledge of the current SINR condition at the receiver.

In our model, we assume closed-loop RA [12]. Therefore, its functionality in the static case is reduced to computing the mean SINR from the SINR histogram (generated by the MAC and channel model) and selecting the MCS with the highest expected throughput at this SINR level. It has to be noticed that this expected throughput differs from the effective rate as computed by the PHY model from Section III-D, as this computes the average rate of the selected MCS, given the SINR distribution.

D. Physical Layer

For a constant SINR value, the effective rate can be computed from the Bit Error Rate (BER) of the selected MCS, the frame length, the number of data bits per symbol of the MCS and the IEEE 802.11 overhead, i. e., headers, preamble, length of the acknowledgement and the duration of the interframe-spaces.

Consequently, the effective rate for a given interference histogram is the mean of the rates at all given SINR values, weighted by their probability.

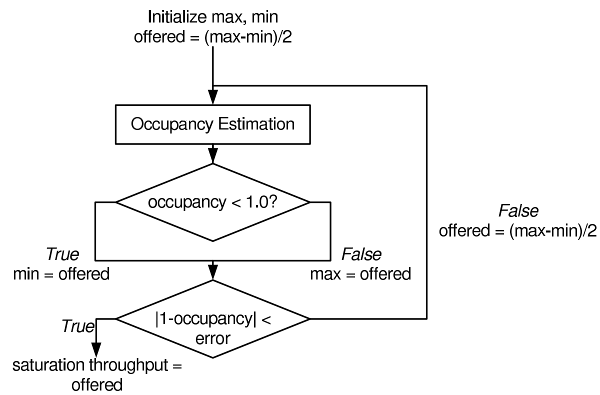


Fig. 3: Capacity estimation with the help of the occupancy estimation model using binary search.

E. Final Model

The effective rate computation requires as input the offered traffic and an initial effective rate per link. The offered traffic per link depends on two parameters: the offered end-to-end traffic in the network and the path selection protocol plus its link metric. While the first parameter is given by the scenario, the path selection protocol and the metric are implementation specific. For WMNs, the amendment “s” of IEEE 802.11 specifies the Hybrid Wireless Mesh Protocol (HWMP) as mandatory path selection protocol and the “Airtime” as mandatory link metric [13].

In our model, the dynamic selection and maintenance of paths is simplified to a static weighted graph, which is used as input for the Floyd-Warshall all-pairs shortest path algorithm. To compute the edge weights, the expected rate $r(i, j)$ of each link is required; these rates are computed once for the optimal case without interference.

Using the output of the Floyd-Warshall algorithm, the offered end-to-end traffic can be converted to the offered traffic per link $o(i, j)$ by going through all selected paths and adding up the corresponding load. Similar, the initial effective rates are selected as the rates under optimal condition, i. e. without interference.

After the iterative process from Figure 1 has converged, the final effective rates $r(i, j)$ and the channel busy fraction $p_{busy}(i)$ are known. Therefore, the fraction of time blocked by and transmitting to its neighbors can be computed as the *occupancy* of the node:

$$occupancy(i) = p_{busy}(i) + \sum_j \frac{o(i,j)}{r(i,j)}$$

The network is in saturation if at least one node has an occupancy greater than 1.0, this node is the bottleneck of the network.

To find the saturation throughput using our model, we search for the offered traffic with $\max_i occupancy(i) = 1.0$ in a binary-search manner as given in Figure 3. With this procedure, the saturation throughput can be estimated within a given error margin.

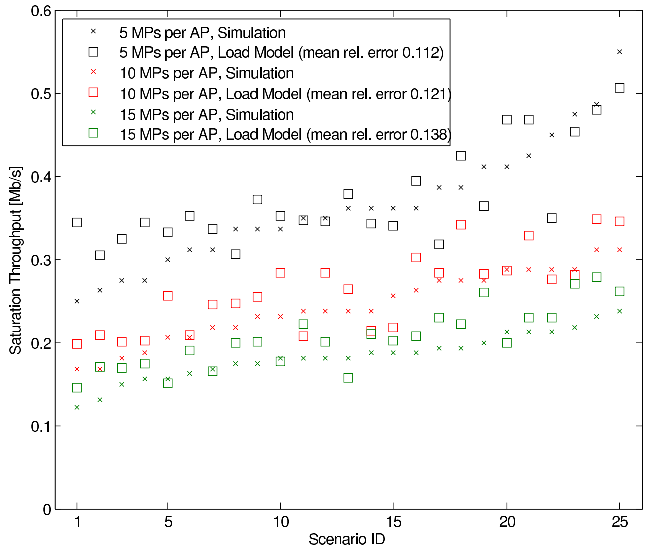


Fig. 4: Saturation throughput of 75 different scenarios, computed using event-based simulation and static IEEE 802.11 model

IV. Evaluation

For the evaluation, we apply the WMN scenario creator from [14]. It is used to generate 25 service areas of 1 km^2 with different shadowing conditions; then, the area is covered with 30 to 35 MPs so that wireless coverage and connectivity of the WMN is ensured.

In the second step, either 2, 3 or 5 nodes are selected to be APs, the remaining nodes are MPs; this results in approximately 15, 10 or 5 MPs per AP and an average path length of about 3, 2.5 and 1.5, respectively.

Traffic is generated in each of the 75 available scenarios by 64 STAs, positioned on a 8x8 equi-distant grid; each STAs requires the same offered traffic, divided in 90% downlink and 10% uplink from/to the Internet, respectively.

To evaluate the accuracy and the complexity of the static IEEE 802.11-based WMN model, the derived capacity is compared to the capacity obtained from an event-driven simulator. In this simulator, the complete IEEE 802.11 protocol stack is implemented, including the same PHY layer abilities as described in Section III-D.

To assure small confidence intervals, one simulation requires 1.5 to 2 hours. As up to 7 successive simulations are needed to estimate the saturation throughput using a similar binary-search method as depicted in Figure 3, it can take 14 hours to compute the saturation throughput using simulation. In contrast, the static model needs on average 5.6 to 8.2 minutes for the complete process, about 3% of the simulator.

Figure 4 compares the saturation throughput of the model with the values obtained by simulation. The mean relative error is below 15% for all different MPs/AP settings. Some outliers can be identified, resulting from the simplifications of the model.

V. Conclusion

The presented static model allows for the efficient estimation of the saturation throughput of a given WMN, taking into account the complex interplay of the different links. The evaluation shows a reasonable mean relative error of less than 15%, measured in different typical WMN scenarios. While this error exceeds that in [10], we have included the existence of MCSs and a RA to select between them. Therefore, our model is appropriate for RNP of state of the art WMNs installations. As a special feature, our model allows for identifying the bottleneck of the network, which can be used to guide the optimization of the network.

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References

[1] J. Laiho, A. Wacker, and T. Novosad, *Radio Network Planning and Optimisation for UMTS.* Wiley & Sons, July 2001.

[2] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” *IEEE JSAC*, vol. 18, pp. 535–547, 2000.

[3] K. Pawlikowski, H.-D. Jeong, and J.-S. Lee, “On credibility of simulation studies of telecommunication networks,” *IEEE Communications Mag.*, vol. 40, pp. 132–139, 2002.

[4] D. Malone, K. Duffy, and D. Leith, “Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions,” *IEEE/ACM Trans. on Networking*, vol. 15, pp. 159–172, 2007.

[5] L. Xiong and G. Mao, “Saturated throughput analysis of IEEE 802.11e edca,” *Compututer Networks*, vol. 51, pp. 3047–3068, 2007.

[6] P. Gupta and P. Kumar, “The capacity of wireless networks,” *IEEE Trans. on Information Theory*, vol. 46, pp. 388–404, 2000.

[7] B. Liu, P. Thiran, and D. Towsley, “Capacity of a wireless ad hoc network with infrastructure,” in *Proc. of the 8th ACM MobiHoc*, pp. 239–246, 2007.

[8] A. Heinrich and S. Feldmann, “Capacity of IEEE 802.11-based ad hoc networks with fairness constraints,” in *Proc. of the 17th IEEE PIMRC*, pp. 1–4, 2006.

[9] J. He, D. Kaleshi, A. Munro, Y. Wang, A. Doufexi, J. McGeehan, and Z. Fan, “Performance investigation of IEEE 802.11 MAC in multihop wireless networks,” in *Proc. of the 8th ACM MobiHoc*, pp. 242–249, 2007.

[10] L. Qiu, Y. Zhang, F. Wang, M. K. Han, and R. Mahajan, “A general model of wireless interference,” in *Proc. of the 8th ACM MobiHoc*, pp. 171–182, 2007.

[11] A. Kashyap, S. Ganguly, and S. R. Das, “A measurement-based approach to modeling link capacity in 802.11-based wireless networks,” in *Proc. of the 8th ACM MobiHoc*, pp. 242–253, 2007.

[12] M. Lacage, M. H. Manshaei, and T. Turletti, “IEEE 802.11 rate adaptation: a practical approach,” in *Proc. of the 7th ACM MSWiM*, pp. 126–134, 2004.

[13] “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,” Nov. 2006.

[14] S. Max, L. Stibor, G. Hiertz, and D. Denteneer, “IEEE 802.11s mesh network deployment concepts,” in *Proc. of the 13th European Wireless Conference*, 2007.