Model-based Radio and Channel Assignment in IEEE 802.11 Wireless Mesh Networks

Sebastian Max, Yunpeng Zang
Department of Communication Networks (ComNets)
Faculty 6, RWTH Aachen University, 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*—Local area wireless networks based on IEEE 802.11 have a cellular topology: Stations associate to one of several access points, which are connected using a wired backbone. As connectivity is only possible close to the access points, a dense infrastructure is needed, resulting in high costs. A Wireless Mesh Network (WMN) replaces the wired backbone by radio: Only few access points are installed; mesh points extend their coverage by forwarding data over wireless hops. Hence, deployment costs are reduced.**

Since the wireless medium has to be shared by the nodes, multi-hop traffic requires a high capacity. Hence, mechanisms which increase the system capacity in wireless mesh networks are needed.

With more than 10 orthogonal channels, IEEE 802.11a provides an excellent foundation for a multi-channel network; furthermore, standardized hardware allows to equip nodes in the WMN with more than one radio. Thus, the problem arises how to plan the channel and radio assignment in a IEEE 802.11-based Multi-Channel Multi-Radio (MRMC) WMN.

In this paper, we first establish and evaluate a model to compute the saturation throughput in a given WMN configuration, taking into account the characteristics of the service area and the MAC and PHY capabilities of IEEE 802.11. With the help of the model, it becomes possible to identify the network bottleneck; This allows the application of a local search optimization algorithm which maximizes the saturation throughput under the constrains of limited channels and radios.

The evaluation shows that the developed algorithm together with the load model does not only increase the saturation throughput, but also the system spectral efficiency, which indicates a more effective usage of the radio resources.

I. Introduction

The standard 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. campus area networks. 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 from the nearby AP multi-hop to a STA and back.

To transport the aggregated traffic of the STAs, the WMN backbone requires more capacity than what is available in a single 20 MHz channel. Therefore, IEEE 802.11a with its multiple orthogonal channels provides an excellent foundation for large-area WMNs. To use the channels efficiently, Multi-Radio Multi-Channel (MRMC) WMNs are deployed: While one radio per node is dedicated to serve the STAs in the Basic Service Set (BSS), one or more radios are available for the mesh backbone.

This work is concerned with this frequency/radio planning of IEEE 802.11-based MRMC WMNs. Depending on the maximum number of radios per node and the number of available radio channels, the MRMC-configuration algorithm has to select for each radio on each node the appropriate channel. Any MRMC-configuration has to fulfill the following constrains:

1) **Radio-to-Channel Assignment:** The number of orthogonal channels that can be assigned to any node is bounded by the number of its radios.
2) **Channel-to-Link Assignment:** Two nodes that communicate with each other directly must share one common channel.
3) **Connectivity:** Each MP in the WMN has to have at least one reliable path to at least one AP.
4) **Load Distribution:** The expected load of the links of a node should be distributed equally so that each link, but also each channel is utilized similarly.

A MRMC-configuration algorithm shall maximize, under these constrains, the WMN's saturation throughput. Due to the limited number of available channels and radios per node, interference between links cannot be completely eliminated; Hence, its effect on the IEEE 802.11 Physical Layer (PHY) and Medium Access Control (MAC) must be minimized.

A. Related Work

Work on MRMC WMNs has evolved during the last years, meeting the demand for capacity increase in WMNs.

One of the first contributions in this field, [1] presents a centralized channel assignment and routing algorithm, which takes the expected link load into account. [2] enhances this work by explicitly including interference between links. While the two mentioned paper use straightforward heuristics to solve the NP-hard channel assignment, [3] presents a tabu-search based algorithm, which also accounts for interference.

In contrast to the work on centralized algorithms, recent contributions propose distributed protocols for the channel assignment. By converting [1] to a distributed solution, the authors of [4] come up with a well-designed distributed protocol. Very interesting work is also done in [5], which is the first paper that takes overlapping channels into account, but does not consider the expected traffic. Very recently, [6] goes beyond this by including congestion-awareness, combined with a simplistic model for the link capacity in a multi-user environment.

All discussed approaches have in common that they neglect two important properties of IEEE 802.11: First, the incapability of the transmitter when determining the channel state, resulting in hidden- and exposed link situations, which should be eliminated by a good MRMC-configuration. Second, the ability of the transmitter to select between different Modulation- and Coding Schemes (MCSs). By neglecting this, the mentioned papers model reception errors by defining a threshold θ for the Signal to Interference plus Noise Ratio (SINR) which must be exceeded for a successful reception. While it is straightforward to extend this to multiple thresholds θ_m for every MCS m, this is not the only mandatory addition: To check if a concurrent transmission is successful, the (in)ability of the transmitter's Rate Adaptation (RA) algorithm has to be included.

B. Contributions & Organization

Our work concentrates on IEEE 802.11-based WMNs which are planned, deployed and maintained by a single operator to provide wireless Internet access to a limited-size and densely populated area. Hence, it can be assumed that (a) the WMN itself is completely stationary during operation, (b) the operator has full control of the radio/frequency settings of each AP and MP, and (c) traffic statistics can be collected.

Under the given assumptions, we restrict ourselves to a central-coordinated optimization of the radio and channel configuration. A novel element of the optimization is the usage of a *load model*, presented in Section II, to judge the performance of a given MRMC-configuration. In contrast to the literature, we do not only consider interference, but also its effect on the IEEE 802.11 channel access method, the Clear Channel Assessment (CCA) and the RA. Hence, we do not minimize interference, but maximize the WMN's saturation throughput.

The optimization algorithm, described in Section III, is based on local search. Using the load model, it becomes possible to identify the bottleneck in the current MRMC-configuration and thus to add radios and channels where needed. Hence, in contrast to existing work, the algorithm does not require every MP or AP to have a pre-defined amount of radios, but improves the radio configuration where needed.

After the presentation of the load model and the MRMC-configuration algorithm, Section IV concludes the paper with the evaluation of the possible gains and limitations of MRMC-WMNs.

II. IEEE 802.11 Load Model for WMNs

The major challenge for a WMN load model are the complex interactions between links. One important property is the *effective rate* $r(i,j)$ of a link from node i to node 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 selected MCS and the overhead of IEEE 802.11. Second, $r(i,j)$ depends on the interference from surrounding nodes. If interference occurs frequently, i selects a more robust MCS, decreasing its effective rate. Therefore, it has to transmit longer for the same amount of data, possibly increasing interference to other nodes. These, in turn, may also decrease their MCS, and so on. Either, this procedure converges or links are blocked completely and stop operating.

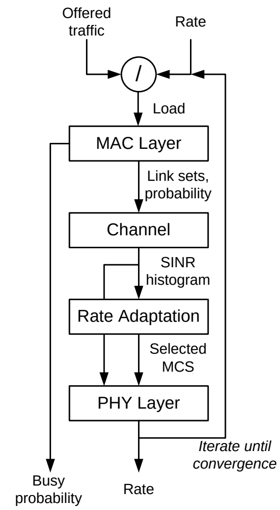


Fig. 1: IEEE 802.11 load model

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. 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 traffic of neighboring nodes.

The major part of the load 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 effective rate $r(i,j)$ gives the load $l(i,j)$ for the link from i to j.
2) The throughput of the IEEE 802.11-MAC in a WMN heavily depends on the transceiver's (in)capably to assess a clear channel at the receiver, using the CCA function. For any link in the WMN, the CCA affects (i) which nodes are blocked by the transmission and (ii) which sets of nodes are able to transmit simultaneously. The computation of (i) and (ii) together with the corresponding probabilities is the task of the MAC model. For this the algorithm enumerates, using a depth-first search, all links that can transmit simultaneously to link (i,j). First, all nodes within a circle of -105 dBm to i and j are stored in a candidate set. Then, the algorithm

identifies nodes that (i) are blocked by the transmitter due to the CCA and (ii) transmit simultaneously. In the second case, two options are possible, creating two children of the search: for a passive and for an active node. If the node is active, the set of candidate nodes is updated to contain only nodes that are not blocked.
The probability of each set is calculated as the product transmission probability of each link, which is the load $l(i,j)$; similarly, the blocking probability $p_{busy}(i)$ is calculated as the sum of loads of links that block (i,j).
3) With the help of a channel model (based on on-site measurements or a model of the propagation conditions) the sets of simultaneous transmissions are converted into SINR values for the links. Together with their probabilities, a SINR distribution for each link is obtained.
4) The Rate Adaptation (RA) model assumes a closed-loop RA that uses the mean SINR to select the MCS. Hence, the mean of the SINR distribution and the MCS resulting in the highest throughput at this mean is selected.
5) The PHY model 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.

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 WMN 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.

In our load 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 WMN is in saturation if at least one node has an occupancy greater than 1.0, this node is the bottleneck of the WMN.

To find the saturation throughput using our load model, we search for the offered traffic with $\max_i occupancy(i) = 1.0$

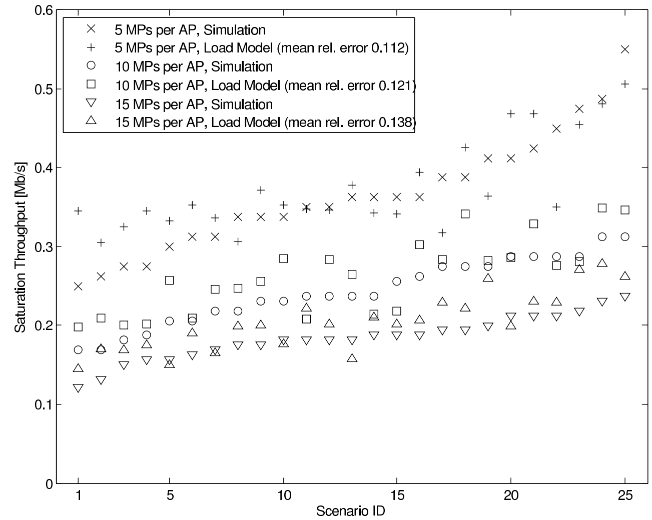


Fig. 2: Saturation throughput of 75 different scenarios, computed using the IEEE 802.11 model and event-based simulation as reference.

in a binary-search manner. With this procedure, the saturation throughput can be estimated within a given error margin.

A. Load Model Evaluation

For the evaluation, we apply the WMN scenario creator from [7]. 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 approximately 3, 2.5 and 1.5, respectively.

Traffic is generated in each of the 75 scenarios by 64 STAs, positioned on a 8x8 equi-distant grid; this models one active user every 125 m. Each STAs requires the same offered traffic, divided in 90% downlink and 10% uplink from/to the Internet to model the typical broadband usage with small requests and large (multi-media) downloads.

To evaluate the accuracy and the complexity of the load model in IEEE 802.11-based WMNs, the derived saturation throughput is compared to the value obtained from event-driven simulation using the openWNS and its implementation of IEEE 802.11 [8]. With this simulator, the saturation throughput estimation in one scenario, using successive simulations with increasing offered traffic, takes around half a day. In contrast, the model needs 5 to 8 minutes for the complete process.

Figure 2 compares the saturation throughput of the model with the values obtained by simulation. The mean relative error,

$$\frac{1}{25} \sum_{i=1\dots25} \frac{|simulation(i) - model(i)|}{simulation(i)},$$

is below 15% for all different MPs per AP settings. Some outliers can be identified, resulting from the simplifications of the model.

III. MRMC - Algorithm

We apply the load model in two different ways: First, to calculate the saturation throughput of the WMN in the current configuration and the occupancy (as defined in Section II) of all nodes under saturation conditions, encapsulated in

$$ComputeSaturationThroughput() \rightarrow (sat, occ).$$

Here, sat denotes the saturation throughput, and occ a matrix with entries between zero and one for the occupancy of each node on each channel at saturation.

Second, the load model is used to compute the occupancy of the nodes only, given the offered traffic per STA o:

$$ComputeOccupancy(o) \rightarrow occ.$$

A. Overview

Initially, each node is equipped with one mesh radio and one BSS radio; all mesh radios are tuned to the same frequency. This represents a dual-radio WMN.

The addition of new radios to nodes is driven by the load model: With its help, the bottleneck of the WMN is identified; clearly, the only way to increase the saturation throughput is to increase the bandwidth of the bottleneck node adding a new radio either to this node or to a node in the neighborhood, lowering the interference. With each added radio, an unused channel is added and selected links are assigned to this channel. The first part of the algorithm is repeated until the bottleneck node and all its neighbors have reached the maximum number of radios. As the restriction of the number of channels is not yet considered, more channels than available might be assigned to the WMN. Therefore, the second part of the algorithm is applied to reduce the number of channels by merging until the final configuration is found.

In the following, we first introduce the network split operation. Then, the two part, channel expansion and channel reduction, are explained in detail.

B. Network Split

The fundamental operation during the addition of radios and channels to the MRMC WMN is the *network split*.This operation adds one more radio to a given node and assigns links of this node to the radio on a new channel without the addition of any other radio to the network. As input it takes the node i, a set of links $L = \{(i, j)\}$ connected to i and a new channel c. During the operation, L is used as a stack: First, a link (p, q) is taken out of L and moved to the new channel c. Then, all links of node q which have been on the same channel as (p, q) are appended to L. This is iterated until L is empty. In this way, node i "splits" the network into two separated networks, one with the old channels and the other one with the new channel.

The split operation preserves connectivity: If the network was connected before the split using $c-1$ channels, it still is connected with c channels: Both parts of the network, the one on the $c-1$ channels and the one on channel c are connected, and the two parts are connected via the new radio of node i.

C. Channel Expansion

Algorithm 1 shows the addition of one radio to the WMN. First, the WMN bottleneck node b, i. e., the node with the occupancy 1 at saturation, is identified with the help of the load model in lines 1 to 4.

Two different options are now possible: Either, the new radio is added directly to node b, enlarging b's bandwidth; or to a node in the near neighborhood, lowering the interference on b by moving links of this node to a new channel.

If b has fewer than the maximum number of radios, we select the first option, as this has the maximum impact on the occupancy of b. If it is not possible to extend b, an alternative node is searched in lines 5 to 14. This search requires a candidate to have traffic on the same channel as b and to be within its reception range; otherwise, the addition of a radio to the candidate would not have an effect on the occupancy of b. Furthermore, the candidate must have fewer radios than the allowed limit.

If more than one candidate exists, the one with the highest cumulated offered traffic is selected; if no candidate exists, there is no possibility to decrease the occupancy of b and the algorithm stops.

After this selection step, the best split choice is calculated. For each possible split, the algorithm computes the occupancy; finally, in line 21 the algorithm selects the split which minimizes the maximum occupancy of b on all channels. If no such split exists, i. e., the current channel assignment without a new radio is already optimal, the algorithm stops.

D. Channel Reduction

As the expansion algorithm does not consider the limited number of available channels, the resulting configuration may have more channels than available. Therefore, the second step reduces the number of channels, preserving the connectivity and the throughput improvements.

Again, we make use of the load model to compute the saturation throughput. Algorithm 2 shows one iteration of the channel reduction from c to $c-1$ channels: After computing the saturation throughput and, more important, the occupancy of each node on each channel, the two least occupied channels c_1 and c_2 are determined; a channel occupancy is measured as the maximum occupancy of any node on this channel.

After finding those two channels, all links from c_1 are reassigned to c_2, reducing the total number of channels by one. Of course, this merging of the two channels will increase mutual interference of links and thus reduce the saturation throughput, as it can be expected from a reduced number of channels.

E. Algorithm Complexity

We measure the algorithm's complexity in the number of calls to the load model. As the channel expansion presents a

Algorithm 1 Channel Expansion

$(sat, occ) \leftarrow$ ComputeSaturationThroughput()
$o \leftarrow$ offered traffic per channel and link (size $c \times n \times n$) if sat is the offered traffic per STA
$c_b \leftarrow \text{argmax}_{c \in C}\ \text{argmax}_{i=1 \ldots n}\ occ(c, i)$
$b \leftarrow \text{argmax}_{i=1 \ldots n}\ occ(c_b, i)$
if b has reached maxRadios **then**
  Find node i on c_b with
  - $o(c_b, i) = \sum_{j=1}^{n} o(c_b, i, j) > 0$
  - i has not reached maxRadios
  - i is in reception range of b

  if No such i exists **then**
    $occ(c_b, b)$ cannot be reduced $\rightarrow$ STOP
  end if
  if More than one candidate exists **then**
    $i \leftarrow$ Node among candidates with highest $o_{c_b}(i)$
  end if
  $b \leftarrow i$
end if
$L \leftarrow \{(b, j) : o(c_b, b, j) > 0\}$
for all subsets L' of L **do**
  Generate new channel c^*
  split(b, L', c^*)
  $occ^{L'} \leftarrow ComputeOccupancy(sat)$
end for
$L^* \leftarrow \text{argmin}_{L' \subseteq L}\ \max_{c=1 \ldots c^*}\ occ^{L'}(c, b)$
if $L^* = \{\}$ **then**
  $occ(c_b, b)$ cannot be reduced $\rightarrow$ STOP
end if
split(b, L^*, c^*)

Algorithm 2 Channel Reduction

$(sat, occ) \leftarrow$ ComputeSaturationThroughput()
$c_1 = \text{argmin}_{c \in C}\ \max_{i=1 \ldots n}\ occ(c, i)$
$c_2 = \text{argmin}_{c \in C \setminus c_1}\ \max_{i=1 \ldots n}\ occ(c, i)$
for all (p, q): channel((p, q)) = c_1 **do**
  channel((p, q)) $\leftarrow c_2$
end for

typical local search algorithm, its complexity can be computed by

$$O\left(\text{number of steps} \cdot \text{complexity of one step}\right)$$

The number of steps is limited by $r \cdot n$ steps, with r being the maximum number of radios and n the number of nodes. In one step, the bottleneck is found (using the load model once), one radio is added, and then all possible network splits are carried out and computed. If the bottleneck is connected to l other nodes, $2^{(l-1)} - 1$ possible splits exist. Hence, the algorithm complexity is $O\left(r \cdot n \cdot 2^l\right)$.

In the worst case, the bottleneck is connected to all other nodes and thus $l = n - 1$; in a planned WMN $l << n$ (and of course $r << n$); thus the exponential factor is constant. During the evaluation, we computed the optimal MRMC-configuration of a WMN consisting of 32 nodes in about 30 minutes. Hence, a optimization of a WMN once per day is feasible.

IV. Evaluation

To evaluate the channel assignment algorithm we use the simulation scenarios and traffic assignment as described in Section II-A.

All MPs and AP are equipped with one radio which is dedicated for the communication to the STAs and back. This radio uses one of three available channels from the license-exempt 2.4 GHz band. BSS to channel assignment is done randomly, optimizations are out of the scope of this paper. The communication in the WMN backbone uses the license-exempt channels above 5 GHz. In the following, we will use the notion (r_{WMN}, c_{WMN}) to abbreviate the number of radios and channels used for the WMN.

The first performance metric is the saturation throughput per STA, averaged over 25 scenarios with the same MPs per AP ratio is used. As in Section II-A, this metric is obtained by simulation using the openWNS [8] simulation platform with its IEEE 802.11 protocol implementation.

Additionally, the *system spectral efficiency*, is used to evaluate the efficiency of multiple channels in a WMN. It is defined as the system saturation throughput of the WMN divided by the allocated bandwidth:

$$\frac{\text{saturation throughput} \cdot n_{STA}}{c_{WMN} \cdot 20\text{e}6\,\text{Hz} + 60\text{e}6\,\text{Hz}},$$

where n_{STA} denotes the number of STAs and the 60e6 Hz represent the three channels dedicated to the BSSs.

A. Lower and Upper Bounds

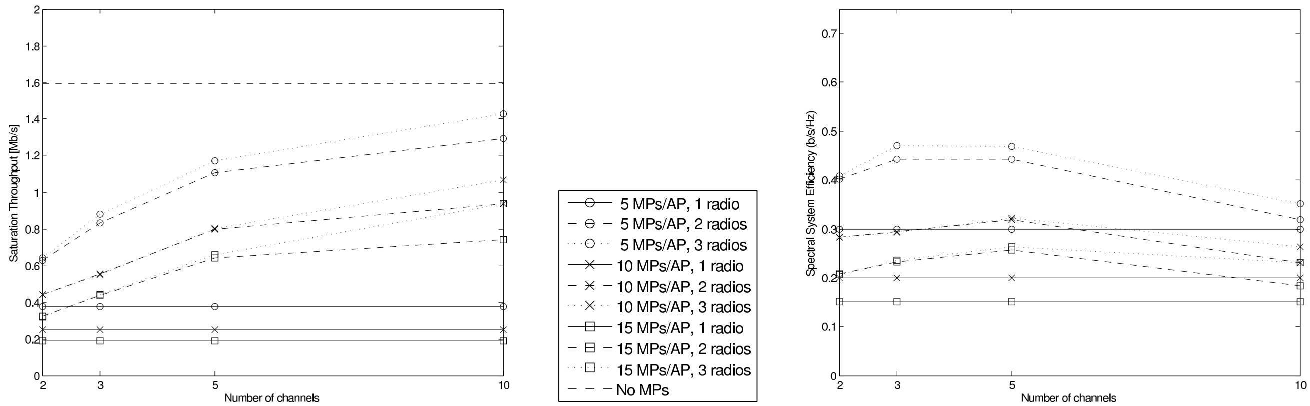
To judge the gain resulting from the addition of radios and/or channels to a WMN, the lower and upper bounds of the saturation throughput are determined first.

The lower bound for the channel assignment algorithm is given by a dual-radio WMN: Each MP and AP has one radio for the BSS and another one for the mesh backbone. To ensure connectivity, all mesh radios have to use the same channel. Hence, the WMN uses a $(1, 1)$-MRMC configuration.

The upper bound is defined by the deployment with the highest installation costs: Instead of a combination of MPs and APs, the access network uses only APs, positioned in the same way as the MPs.

Figure 3a shows, in dashed lines, the lower and upper bound saturation throughput. As expected, the saturation throughput of the lower bound configuration heavily depends on the ratio of MPs per AP: Starting from 0.2 Mb/s using 15 MPs per AP, the saturation is doubled at 5 MPs per AP. Still, the wireless mesh backbone limits the saturation as the upper bound of 1.6 Mb/s shows.

The system spectral efficiency in Figure 3c contains the lower bounds only; the upper bound is omitted because efficiency comparison is meaningful only with identical system costs, i. e., using the same MPs per AP ratio and different radio/channels.



(a) Saturation Throughput (b) Legend (c) System Spectral Efficiency

Fig. 3: Evaluation results for different MPs per AP ratios.

B. Saturation Throughput

The saturation throughput results of the three different MPs per AP configurations are given as solid lines in Figure 3a.

It is obvious that an increase of the channels dedicated to the WMN increases the saturation throughput: The addition of one radio and one channel to reach a $(2, 2)$-MRMC configuration nearly doubles the saturation throughput. The next enhancement, a $(2, 3)$ configuration, results in a 2 to 2.5-fold increase; the $(2, 5)$ and $(2, 10)$ configurations show approximately an increase by a factor of 3 and 3.5, respectively.

Using three instead of two radios for the WMN backbone, i. e., a $(3, x)$-configuration, provides no advantage for $x \leq 5$. Only the $(3, 10)$ shows a 10 to 15% increase, depending on the ratio of MPs per AP.

C. System Spectral Efficiency

Figure 3c shows the average system spectral efficiency for 5, 10 and 15 MPs per AP. Similar to Figure 3a, the values are given for the dual-radio WMN; this case has a system spectral efficiency independent from the number of WMN channels, as only one channel can be used by the WMN radio to ensure connectivity of the mesh.

In comparison to the dual radio WMN, the system spectral efficiency is increased when using either 2 or 3 WMN radios. For all ratios of MPs per AP, the maximum efficiency is reached using 5 WMN channels, exceeding the dual radio case by more than 50%. Thus, it becomes clear that the available bandwidth of $5{\cdot}20{+}60\,\mathrm{MHz}$ is used more efficiently due to the reduced number of hidden- and exposed nodes in comparison to the $20 + 60\,\mathrm{MHz}$ in the dual radio case.

If less than 5 WMN channels are available, not all interfering nodes can be placed onto different channels and thus benefits of MRMC-WMNs cannot be exploited completely. With 10 WMN channels the system spectral efficiency decreases because (a) they cannot be assigned efficiently to only 2 or 3 radios and (b) the spatial separation of links using the same channel is large enough to avoid any interference even with less than 10 channels.

V. Conclusion & Future Work

In this paper we propos a radio and channel assignment algorithm that does not only decrease interference between links, but strives for an improvement of the MAC layer throughput. This is achieved by the inclusion of a detailed IEEE 802.11 load model that allows for an estimation of the saturation throughput of a given WMN, taking into account the complex interplay of the different links. Performance evaluation via simulation shows how the local search algorithm, based on the load model, is able to improve both saturation throughput and system spectral efficiency.

Improvements of the method are possible. First of all, the current algorithm should be converted to a distributed version to be able to adapt to local changes more timely than the centralized version.

Acknowledgments

The author would like to thank Prof. Dr. -Ing. B. Walke for his support and friendly advice to this work.

References

[1] A. Raniwala, K. Gopalan, and T. Chiueh, “Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks,” *SIGMOBILE Mob. Comput. Commun. Rev*, vol. 8, pp. 50–65, 2004.

[2] K. N. Ramachandran, E. M. Belding, K. C. Almeroth, and M. M. Buddhikot, “Interference-aware channel assignment in multi-radio wireless mesh networks,” in *IEEE INFOCOM 2006*, 2006, pp. 1–12.

[3] A. P. Subramanian, H. Gupta, and S. R. Das, “Minimum interference channel assignment in multi-radio wireless mesh networks,” in *IEEE SECON*, 2007, pp. 481–490.

[4] A. Raniwala and T. Chiueh, “Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network,” in *IEEE INFOCOM*, vol. 3, 2005, pp. 2223–2234 vol. 3.

[5] B.-J. Ko, V. Misra, J. Padhye, and D. Rubenstein, “Distributed channel assignment in multi-radio 802.11 mesh networks,” in *IEEE WCNC*, 2007, pp. 3978–3983.

[6] A. H. M. Rad and V. W. Wong, “Congestion-aware channel assignment for multi-channel wireless mesh networks,” *Computer Networks*, vol. In Press, Corrected Proof, pp. –, 2009.

[7] S. Max, L. Stibor, G. Hiertz, and D. Denteneer, “Ieee 802.11s mesh network deployment concepts -invited paper-,” in *European Wireless*, 2007, p. 7.

[8] “Open wireless network simulator (openwns),” http://www.openwns.org.