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Performance model for IEEE 802.11s wireless mesh network deployment design

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Abstract

This paper presents a performance model developed for the deployment design of IEEE 802.11s Wireless Mesh Networks (WMN). The model contains seven metrics to analyze the state of WMN, and novel mechanisms to use multiple evaluation criteria in WMN performance optimization. The model can be used with various optimization algorithms. In this work, two example algorithms for channel assignment and minimizing the number of mesh Access Points (APs) have been developed. A prototype has been implemented with Java, evaluated by optimizing a network topology with different criteria and verified with NS-2 simulations. According to the results, multirate operation, interference aware routing, and the use of multiple evaluation criteria are crucial in WMN deployment design. By channel assignment and removing useless APs, the capacity increase in the presented simulations was between 230% and 470% compared to a single channel configuration. At the same time, the coverage was kept high and the traffic distribution fair among the APs.
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Keywords: Wireless mesh network; IEEE 802.11s; Deployment design; Performance model; Multirate; Metrics

1. Introduction

The IEEE 802.11 Wireless Local Area Network (WLAN) technologies [17] are in key position for providing wireless Internet access. When implementing city wide WLANs, the network deployment costs are increased due to number of WLAN Access Points (APs) needed to provide coverage. Mesh networking is one of the latest WLAN technologies for providing large network coverage with low deployment cost, as well as for increasing network flexibility and robustness.

Fig. 1 presents an example of the IEEE 802.11s Wireless Mesh Network (WMN) topology. WMN is formed by devices called *mesh points* that contain WMN functionality. Mesh points can be *mesh portals*, *mesh APs* or *mesh portal APs*. It is also possible that a mesh point does not have neither AP nor portal functionality. Mesh portals have wired connections to a core network, while other mesh points rely on wireless connections when forwarding packets toward their destinations. Extending coverage without wired connections to each AP keeps deployment costs down. WMN APs often use several radios to reduce interference and to increase network capacity. Also simultaneous use of multiple wireless technologies with different frequency ranges, such as IEEE 802.11g, and IEEE 802.11a, is common [24].

A Wireless Internet Service Provider (WISP) has multiple objectives when designing a WMN deployment. To provide predictable Quality of Service (QoS) for the user should always be a key objective, but also the deployment cost, service area, number of users, and resource utilization have to be considered.

WMNs have unique properties compared to infrastructure and ad hoc WLAN technologies that make traditional deployment design methods inadequate [45]. In WMN, devices other than terminals are static and methods developed for ad hoc networks do not fit WMNs due to low device mobility [27]. For systematic WMN deployment, a method to estimate the WMN performance is needed. WMN properties, such as interference, multihopping and WLAN multirate operation, make the estimation of the performance impracticable without adequate tools and methods.

This paper presents a *performance model* developed for the deployment design of IEEE 802.11s WMNs. This kind of

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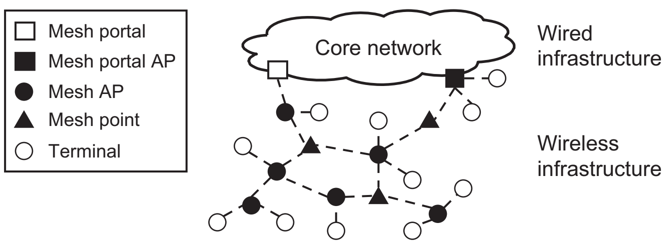


Fig. 1. An example of a IEEE 802.11s WMN topology.

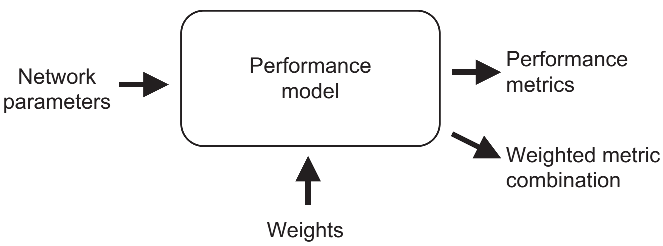


Fig. 2. Usage of the performance model.

approach using multiple design criteria has not been proposed earlier. The usage of the model is described in Fig. 2. The model estimates the performance of WMN based on a set of parameters that describe the network and its configuration. These parameters contain information about the devices, their locations, parameters, signal propagation, and network routes. The output of the performance model is seven *metrics* to estimate individual physical characteristics of the WMN performance. As an output the model also provides a weighted combination of the metrics for a simultaneous use of multiple evaluation criteria in WMN optimization. The performance model can be used by optimization algorithms e.g. for channel assignment, and node placement optimization. The performance model metrics can also be used for WMN performance analysis, and user QoS estimation.

As an example, two optimization algorithms that utilize the model have been developed to prove the model usability. The first is a genetic algorithm for optimizing the WMN channel assignment. The second algorithm allows WISP to prune the network by removing the unusable mesh points. A full scale prototype implementation of the performance model and the algorithms is also presented. The model and algorithms have been evaluated by optimizing a network topology with different criteria and verified with NS-2 simulations.

The paper is organized as follows. Section 2 describes the challenges in the WMN deployment design and related research is presented in Section 3. The performance model that have been developed is presented in Section 4. The two optimization algorithms are described in Section 5. Section 6 presents a prototype implementation. The operation and performance of the developed algorithms is evaluated in Section 7 and the final section presents the conclusions.

2. Challenges on WMN deployment design

For WMN deployment, the amount, type, and locations of network devices has to be selected, as well as the used equipment. The device parameters, such as transmission power, frequency channel and routing method, have to be defined. There is no direct relation between the design objectives and the possible choices. Furthermore, all these decisions affect the WMN performance. In this context, the WMN performance refers to the characteristics of the network including the network capacity, coverage, cost, and user QoS.

Part of the WMN capacity is needed for forwarding traffic of neighbor APs and the interference caused by usage of same or adjacent channels [1]. Interference can be categorized to intra-flow and inter-flow interference. Intra-flow interference exist when a route contains multiple hops and it is caused by consecutive links to each other within a same flow. Using same channels along the route decreases the flow throughput when the number of hops increases [1,42,36]. Situation is improved by limiting the number of hops from any terminal to a mesh portal [42,25]. Inter-flow interference depends on spatial reuse in the network. Both interference types can be minimized with network topology design, channel assignment and routing. Devices change the used modulation and transmission rate when signal quality decreases to improve bit error rate. This multirate operation significantly affects the network capacity and must be taken into account in both routing and capacity estimation.

Most suitable routing methods for WMNs are based on proactive hop-by-hop routing [27,45]. Traditionally, routing has been based only on hop count but this does not capture the interference and varying link capacity. With an effective routing, it is possible to avoid interference hotspots and use high capacity links. Routing should also use stable attributes based on the network topology to ensure routing stability. Routing sensitive to fluctuating attributes, such as traffic load, cause route instability [45].

WMNs have properties that make it difficult to use resources effectively. IEEE 802.11s WMN is inherently unfair for APs due to interference, multihopping, and the operation of the IEEE 802.11 Medium Access Control (MAC) protocol [5,44,37]. In WMN, APs closer to the mesh portal require more bandwidth to forward packets of other APs. However, the IEEE 802.11 MAC provides roughly equal amount of transmission opportunities to each station regardless of its type. Unless fairness is enforced, APs that have a higher number of hops to a mesh portal have a, respectively, lower capacity. This was shown e.g. by Sridhara et al. in [38]. According to their research on WMN performance, there was a clear distinction between user locations that were inside the network coverage and those where adequate QoS was provided. Taking fairness into account allows to minimize interference soundly and provide capacity for APs that require it most.

Two requirements exist for selecting the WMN deployment with the maximum performance according to designers preferences. These are (1) a mechanism to select the importance of each design objective and (2) tools to use this information both in deployment design and WMN optimization.

3. Related research

Earlier published research on WMN deployment design has concentrated into methods to use of multiple radios and advanced antennas, advanced routing, optimization algorithms, evaluating WMN capacity, and develop MAC modifications. Generic approaches to handle multiple optimization criteria in WMN deployment design do not exist and the following related proposals deal with a limited part of the field. Modifying the MAC protocol is one method to increase WMN performance but it does not remove the need for WMN deployment design. Methods in this work are designed for IEEE 802.11s, and can be generalized for MAC protocols retaining the basic nature of IEEE 802.11.

In [9], Das et al. propose to increase the number of radios and available channels to increase network throughput. Multiple radios have also been proposed by Alicherry et al. in [2]. According to their results, there is a practical limit of three radios, after which there is no additional gain. However in [34], Robinson et al. have made experiments on WMN testbed to evaluate the use of multiple radios and the effect of channel separation. During their experiments, the authors concluded the practical limit of two radios for a single node. Furthermore, the interference between radios affects the required channel separation. Similarly as presented in our previous work [43], the authors show that using a single radio, there exists only minor interference with channel separation of four channels. According to Robinson et al., when the number of radios is increased, also larger channel separation is required.

Usage of directional antennas allows to increase spatial reuse and minimize the interference. Exploiting directional antennas has been proposed by Stine [39] and Li et al. [28]. In [15], Hsiao and Kung developed a design method for WMN topology layout with directional antennas. Directional antennas have lots of potential but they also create challenges for the physical layer, MAC protocol, and routing [39,28]. Our approach is to support the usage of multiple radios and directional antennas. Possibility to use a selected routing algorithm allows also antenna aware routing.

In [11], Duffy et al. have presented an analytical model based on finite-load Markov chain to estimate the throughput of terminals when traffic flows are known. The proposal requires detailed knowledge of terminal traffic flows, which is difficult in a small scale network such as WMN. The authors propose to use IEEE 802.11e TXOPs [18] according to the capacity information to ensure fairness in the network. We consider prior knowledge of terminal traffic flows too restricting for WMN deployment.

In [21], Jun et al. have developed a concept of a *collision domain* that describes the interaction of interfering nodes in WMN. The authors have described how to estimate the WMN capacity with the concept but no algorithm is presented. In this work, we have used the collision domain concept from [21] for developing our capacity estimation algorithm for the performance model.

Jun et al. have also analyzed several queuing schemes to achieve WMN fairness in [23]. The authors state that the simple method of separating original and relayed traffic with adequate weights does not achieve ideal fairness. Ideal fairness requires per flow queuing. Our approach is compatible with per flow queuing if such queuing functionality exist in the devices.

Authors of all optimization algorithms described below, as well as Roy et al. [35], state the importance of advanced routing mechanisms. Routing for WMNs have been studied e.g. in [27,16,45,4]. Our proposal gives a possibility to select any routing mechanism to enable performance estimation and optimization with various routing mechanisms.

Heuristics for minimizing the interference by channel assignment have been proposed by Tang et al. [40] and Ramachadran et al. [30]. Both approaches use an interference graph and a centralized algorithm that minimizes the interference according the graph. Das et al. have proposed two mixed integer linear programming models for the same purpose in [9]. Moreover, in [13] Greve et al. have proposed integer linear program formulation and used the collision domain concept from [21]. The authors developed algorithms for distributing the neighbor nodes over wireless interfaces and for distributed channel assignment to minimize the interference. A greedy heuristic for traffic independent channel assignment is proposed by Marina et al. [29]. They define set of constraints and use their algorithm to check whether there exists a solution where interference is below the defined limit. The previous interference minimization methods maximize the network capacity but it is not known how this capacity is divided in the network.

Optimization of WMN channel assignment using load balancing based approaches have been presented by He et al. [14], and Raniwala et al. [33,31]. Both use long time traffic trends to estimate capacity need in different parts of the network. Then, a heuristic is used to equally divide load between APs in the area. In [32], Raniwala et al. have also developed a distributed algorithm for load aware channel assignment. Load aware channel assignment enables the use of resources where they are actually needed. Our performance model contains a weighted fairness metric for the same purpose. However, compared to the related proposal, the performance model allows both to distribute load and maximize WMN capacity according to users preferences.

Alicherry et al. have proposed a linear programming model for joint channel assignment and routing in [2]. Their approach optimizes the overall network throughput subject to fairness constraints. Using a tight dependence between routing and channel assignment, the otherwise elegant proposal limits itself to its defined routing method.

Instead of using a single channel for each interface as done in the previous approaches, it is possible to use multiple channels simultaneously to forward packets between the nodes. This requires modifications to the MAC protocol but allows to increase bandwidth between two nodes as shown e.g. by Kyasanur et al. [26]. Although this allows the use of all frequency resources it does not remove the need for channel assignment between the network nodes. In this paper, each interface is assumed to use a single channel assigned by the network designer.

Three heuristic algorithms for optimizing the placement of mesh portals based on linear program have been proposed by Chandra et al. [6]. Another integer linear program and a polynomial time near-optimal algorithm for the same purpose has been proposed by Aoun et al. [3]. Both approaches require prior knowledge of the traffic flows and aim to strategically place a minimum number of mesh portals to satisfy the capacity demand.

Using a genetic algorithm for mesh network optimization in radio access networks has been proposed by Ghosh et al. [12]. Their optimization target is cost of deployment versus link reliability in the network.

The presented approaches focus on one or two optimization criteria with the expense of other network characteristics. As an exception, Kodialam et al. [24] identify that there exists multiple design criteria for WMNs. They developed two link channel assignment schemes based on a linear programming formulation that is solved using a fast primal–dual algorithm. Their proposal is able to optimize a single objective function at a time but no generic method for dealing with the multiple metrics is provided.

Based on the earlier work, the question what to optimize when designing WMN deployment still remains. Our approach is to define (1) a set of metrics that work as evaluation criteria for WMN and (2) a weighted combination of the metrics for a simultaneous use of multiple evaluation criteria in WMN optimization.

4. WMN performance model

The performance model provides information about WMN using the metrics. The performance model metrics are *WMN capacity*, *goodput*, *AP fairness*, *coverage*, *deployment cost*, *mean service capacity*, and *service fairness*. These metrics have been designed to profile the internal state of the network with a high abstraction level. Metrics are orthogonal except for the mean service capacity and service fairness that were added to give derived information about user QoS. Performance model and algorithms support the use of multiple radios, WLAN multirate operation and usage of user defined routing metrics.

4.1. Input parameters for the performance model

Input parameters required by the performance model are described in Table 1. Parameters can be collected from existing WMN or they can model the network deployment plan. With these parameters, the performance model can capture the information of the WMN radio device parameters, adapters, cables, antennas, propagation models, and network routes. Requiring the routes in input parameters allows usage of any routing method. For estimating coverage and service capacity, device parameters for a *reference terminal* need to be defined. The reference terminal portrays a users terminal.

4.2. WMN capacity metric

In this paper, WMN capacity is defined as the sum of capacities of the WMN users calculated from successfully received packets. Since the real amount of successfully received user packets can only be determined by a measurement or a detailed network simulation, a method to estimate the capacity with adequate accuracy is needed. The capacity estimation is done with the developed ESTIMATE-MESH-CAPACITY algorithm, the pseudo code of which is presented below. Input parameters are explained in Table 1 and other notations in Table 2.

```
ESTIMATE-MESH-CAPACITY
for each node n ∈ S
  Find route to n_core
end for each
for each node n ∈ S
  for each link l ∈ RT(n, n_core)
    T[l] ← T[l] + B/B_l[l]
  end for each
end for each
for each link l ∈ E
  C[l] ← ∅
  for each node n ∈ V
    if interf(n.channel, l.channel) and
    (dist(n, l.end1) < r_i(n, l.end1) or
    dist(n, l.end2) < r_i(n, l.end2))
    C[l] ← C[l] ∪ E[n]
    end if
  end for each
end for each
for each link l ∈ E
  TC[l] ← 0
  for each link l2 ∈ C[l]
    TC[l] ← TC[l] + T[l2]
  end for each
end for each
for each node n ∈ S
  bottleneckLinkTraffic ← 0
  for each link l ∈ RT(n, n_core)
    if TC[l] > bottleneckLinkTraffic
      bottleNeckLink[n] ← l
      bottleneckLinkTraffic ← TC[l]
    end if
  end for each
end for each
for each node n ∈ S
  capacity[n] ← B/TC[bottleNeckLink[n]]
end for each
meshCapacity ← 0
for each node n ∈ S
  meshCapacity ← meshCapacity + capacity[n]
end for each
```

Before using the ESTIMATE-MESH-CAPACITY algorithm, the WMN topology is altered by adding one traffic source S node close to each mesh AP. These nodes represent the terminals in the network. In the model, real terminals are not traffic sources because their locations and movements are not known.

This topology simplification does not alter the results significantly because the user terminals have much lower antenna gains and receiver thresholds. Terminals also associate to AP with the strongest signal. Thus, they are close to mesh APs when considered in the scale of the whole WMN. Also, the

Table 1
Input parameters required by the performance model

G	Graph $G = (V, E)$, where V is the set of nodes and E is the set of links in WMN
$location(n)$	Location of node $n \in V$
$RT(n_1, n_2)$	Links in route between nodes n_1 and n_2
$interf(c_1, c_2)$	Function returns true if frequency channels c_1 and c_2 cause interference to each other
$r_i(n_1, n_2)$	Interference distance from n_1 to n_2
$B_l[l]$	Link rate of link $l \in E$
$B_t(n, location)$	Link rate between AP n and the reference terminal in *location*
c_i	Cost of mesh point type i
c_c	Cost of cable for mesh points per meter
c_l	Length of cable for mesh points
p_i	Significance value of metric i

Table 2
Notations used in the ESTIMATE-MESH-CAPACITY algorithm

$E[n]$	Links of node n
S	Set of traffic sources in the network
$T[l]$	Link utilization for each link $l \in E$
$C[l]$	Links in the collision domain of link $l \in E$
$TC[l]$	Medium utilization in the collision domain of link $l \in E$
n_{core}	Node $n \in V$ that represents the core network
B	Selected nominal link rate of the network
$dist(n_1, n_2)$	Physical distance between nodes n_1 and n_2

traffic of each individual terminal is low compared to traffic of mesh points and as a whole the traffic concentrates to the vicinity of the mesh APs. However, the simplification relieves the algorithm from considering terminal locations, which cannot be known in advance.

The ESTIMATE-MESH-CAPACITY algorithm has three main phases that are (a) routing, (b) finding bottleneck links with the help of collision domains, and (c) estimating upper limits for mesh AP capacities.

The routing phase (a) contains lines 1–8. First, routes are searched (lines 1–3). Routes are needed only between each traffic source and a core network. Most of the traffic in WMN flows between terminals and the core network. Thus, traffic between terminals can be ignored in capacity estimation without significant loss of accuracy. The implementation uses the Floyd–Warshal algorithm [8] to find routes in the network. The basic Floyd–Warshal uses the hop count as the routing metric and finds the shortest path routes in the whole network. Also other routing methods can be used.

Next, traffic flows are assigned to the network (lines 4–8). The algorithm goes through the routes from each traffic source to the core network and increases the link utilization of each traversed link using the T array. The amount of traffic added to link l is the selected nominal rate of the network, divided by the rate of link l. Thus, the link utilization level of link l is dependent of the link rate $B_l[l]$. The nominal rate of the network B can be selected freely.

The finding bottleneck links phase (b) contains lines 9–33. First, a collision domain is searched for each link (lines 9–18). Fig. 3 illustrates a collision domain of a link that consists of all links sharing the communication resource with either one of the link endpoints. Mutually interfering frequency channels can be defined using the *interf* function according to the selected radio technology. In the evaluation, the *interf* function is defined with channel separation of five channels. Thus only channels 1, 6, and 11 are allowed. Three values are used because there exist only three completely non-overlapping channels in IEEE 802.11b, g standards (in Finland). When IEEE 802.11a is used, the channel separation can be selected according to the number of allowed non-overlapping channels.

The size of the collision domain affects the capacity because link capacity is divided between all traffic in the collision domain. This approach considers links as undirectional. Then, the total medium utilization for the collision domain of each link is calculated (lines 19–24), and a bottleneck link is searched for each traffic source (lines 25–33).

The estimating upper limits phase (c) contains lines 34–40. When the bottleneck link of a traffic flow is known, an upper limit for the capacity of each traffic source is calculated by dividing the nominal rate of the network by the total medium utilization in the collision domain of the bottleneck link (lines 34–36). After this step the theoretical capacity limit (*capacity*) is known for each AP in the WMN to use for serving terminals. Finally, the total capacity (*meshCapacity*) is the sum of AP capacities (lines 37–40).

Fig. 3 contains also an example of capacity calculation for a small network. The example network contains two mesh portal APs, two mesh APs, and four traffic sources. Nodes are assumed to be inside the interference range of each others. Figure uses a notation $B_l : T_l : TC_l$. It is assumed that the link rate of link l_1 is $B/5$ and the link rate of link l_2 is $B/3$. The values of T_l are calculated with the ESTIMATE-MESH-CAPACITY algorithm. Since all nodes are within the same collision domain, TC_l is same for all nodes and the capacity limit $capacity[n]$ for all APs is $B/17$. When the network is larger, all nodes are not in the same collision domain and the importance of finding the bottleneck link increases. However, the basic mechanism works as presented in the example.

The algorithm supports the usage of multiple radio interfaces in the same mesh point. The implementation requires that the network graph $G = (V, E)$ is altered by representing each radio interface as an individual node in the node set V and adding a link between all interfaces of nodes to the link set E. Other modifications are not required.

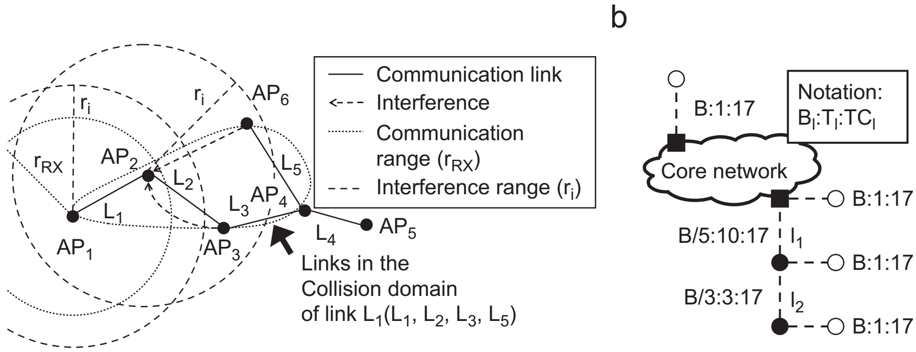


Fig. 3. (a) Collision domain of link L1 and (b) an example of capacity calculation.

Table 3
The ESTIMATE-MESH-CAPACITY algorithm complexity

Lines	Explanation
1–3	Floyd–Warshal finds routes in $O(n^3)$
4–8	Each route can have n nodes $\rightarrow O(n^2)$
9–18	Max number of links is $n^2 \rightarrow O(n^3)$
19–24	Max number of links in $C[l]$ is $n^2 \rightarrow O(n^3)$
25–33	Each route can have n nodes $\rightarrow O(n^2)$
34–36	$O(n)$
37–40	$O(n)$

The ESTIMATE-MESH-CAPACITY algorithm is run in $O(3n^3 + n^2 + 2n)$ time as shown in Table 3. In practice, the graph representing WLAN network is sparse and the number of links is not even close to n^2. Thus, the actual runtime is, respectively, lower.

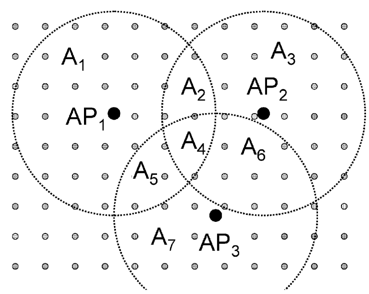
4.3. Goodput metric

The WMN capacity depends on the number of mesh portals in the network. Thus, it is not an ideal metric if the optimization algorithm is allowed to change the number of mesh portals. The goodput metric is designed to represent the interference level in the network. It is created from the capacity metric by dividing it with the maximum amount of capacity of mesh portals. Thus, the goodput metric is independent of the number of mesh portals.

4.4. Coverage metric

The WMN capacity metric favors topologies with a low number of hops and low coverage. Thus, coverage must also be considered. The coverage is defined as the size of the physical area where a terminal has a route to the core network. The area depends on the locations of APs but more importantly on the amount of APs that have a route to the core network.

Accurate and efficient estimation of coverage is difficult because APs have partially overlapping coverage areas. The size of coverage areas also differ depending on AP device parameters. Coverage calculation is done in two steps to support iterative channel assignment algorithms. During the development it was proven to be significantly faster than calculating coverage completely with each iteration if the locations of mesh points are fixed.



Affected areas for each AP

Area	AP_1	AP_2	AP_3
A_1	True	False	False
A_2	True	True	False
A_3	False	True	False
A_4	True	True	True
A_5	True	False	True
A_6	False	True	True
A_7	False	False	True

Fig. 4. Example of coverage calculation. Grid presents possible terminal locations.

The first coverage calculation step estimates the coverage of each area in the network where the set of available APs is different from every other area. An example with three APs is presented in Fig. 4 that contains seven distinct areas. Coverage areas are found out by creating a grid of possible terminal locations. Each terminal location belongs only to a single area and the size of the area is the number of terminal locations belonging to the same area.

The second coverage calculation step is run when APs that have routes to the core network are known. This can be e.g. with each iteration of the optimization algorithm. The total coverage is calculated as the sum of included area coverages. Any particular area is included only if at least one of APs affecting to the area has connection to the core network. Fig. 4 shows how example APs affect to the areas. Assuming that AP_1 and AP_3 have connection to the core network, the total area is the sum of areas A_1, A_2, A_4, A_5, A_6, and A_7.

The first coverage calculation step is executed only once. The running time of the first step is $O(nXY)$, where X and Y define the size of the grid. Runtime of the second step is $O(nA)$, where A is the number of areas. Similarly as with the number of links, the amount of areas is limited because WLAN is sparse in practice.

4.5. AP fairness metric

Fairness represents how equally capacity is divided between traffic sources in the network. Without considering fairness, both coverage and capacity of the network can be high but there still exist areas where APs are practically useless.

To calculate fairness, the Jain's fairness index [19] is used. It is defined as

$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2}. \tag{1}$$

In (1), n is the number of flows, and x_i is the rate of flow i. Fairness index results in a value between 0 and 1 that is intuitive, scale independent, and continuous. WMN fairness is calculated by replacing x_i with *capacity*(n) values from line 35 of the ESTIMATE-MESH-CAPACITY algorithm. Fairness calculation is run in $O(n)$.

A network designer may wish to assign more capacity for certain areas in the network. For these cases, a weighted fairness is a metric that enables the network designer to give a proportional weight to each mesh AP. The equation

$$f = \frac{(\sum_{i=1}^{n} x_i/w_i)^2}{n \sum_{i=1}^{n} (x_i/w_i)^2} \tag{2}$$

is used to calculate the weighted fairness. The equation is developed from (1) by dividing the node capacity with weight w_i. Weighted fairness provides the same properties as the fairness metric.

4.6. Deployment cost metric

Deployment cost depends on the number and type of nodes, as well as the locations of mesh portals due to required cable length. The deployment cost (C) is calculated using equation

$$C = c_i n_i + c_c c_l, \tag{3}$$

where c_i is the cost of individual node of type i and n_i is the number of such nodes. Variable c_l represents the length of the cable required to provide Internet connection to each mesh portal, and c_c is the cost of the cable per meter. More complicated equation can be used if deployment uses e.g. different types of cables. The cost calculation is run in $O(n)$.

Deployment cost can also be used with channel assignment by allowing nodes to be switched off by the optimization process. Such nodes can be removed from the network and their deployment cost is saved.

4.7. Mean service capacity and service fairness metrics

Two additional metrics, mean service capacity and service fairness, were developed to further analyze user QoS level in the network. Service capacity in any particular location is calculated as presented in Fig. 5. First, the set of mesh APs that the terminal can associate to is determined. The possible service capacity in a particular location when the terminal is using AP_x is derived as

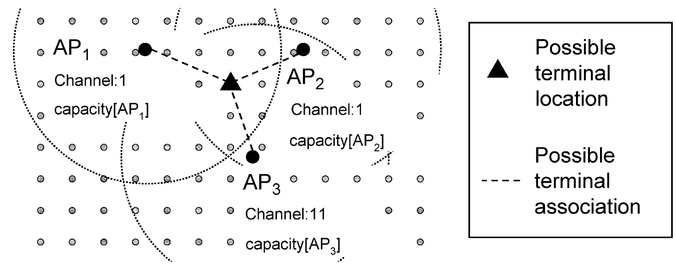


Fig. 5. Service capacity calculation.

$$capacity_s[location, AP_x] = capacity[AP_x]\frac{B_l[link(AP_x, location)]}{B[AP_x]}, \tag{4}$$

where $B_l[link(AP_x, location)]$ is the link rate that a terminal would have in the particular location and $B[AP_x]$ is the maximum link rate of AP_x. The ESTIMATE-MESH-CAPACITY algorithm calculates the *capacity*$[AP_x]$ assuming that the terminal location is close to the AP, thus the link rate between terminal and AP is maximum. Eq. (4) estimates the terminal capacity taking the actual terminal link rate into account. This is accurate assuming that APs limit the capacity used by terminals. Otherwise, the equation is slightly optimistic. The terminal also causes interference to APs, which balances the result.

The service capacity in a particular location *capacity*$_s$ [*location*] is further calculated as a sum of the highest service capacities from each channel. Terminal in any particular location may have multiple APs to associate with but only one can be used from each channel.

The mean service capacity metric is calculated as a mean of service capacities in all locations where service capacity is positive. This makes the service capacity metric independent of the network coverage. The service fairness metric is calculated with (1) by using *serviceCapacity* values in the place of variable x_i. The running time of the service capacity calculation is $O(nXY)$, where X and Y define the size of the grid.

4.8. Combining multiple metrics into network fitness

Metrics presented in the previous sections are usable as such for network analysis and optimization. However, in some cases it is beneficial to have a single metric value that represents the state of the network. For this purpose, a *fitness* is created from a set of metrics using the process described below. First, the user must select which metrics are included in the fitness calculation. Then, each included metric is weighted using a significance value that represents the importance of a particular metric.

To make metrics comparable, the value ranges of each metric must be the same. Goodput, AP fairness, coverage, and service fairness metrics can easily be presented with values between zero and one. The rest of the metrics are converted

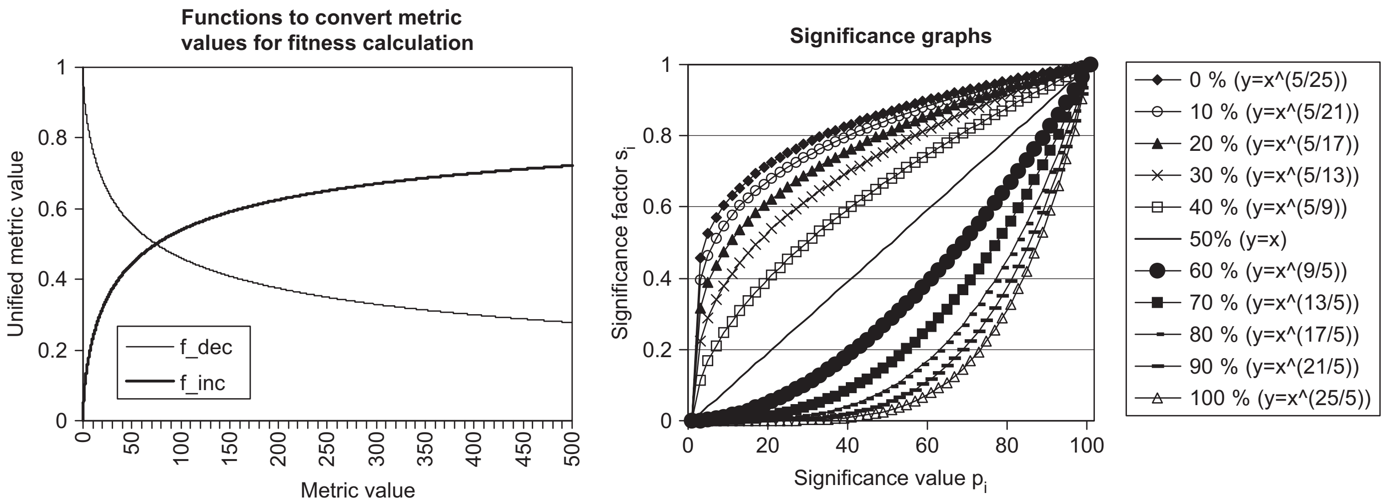


Fig. 6. Functions to convert metric values for fitness calculation and significance graphs.

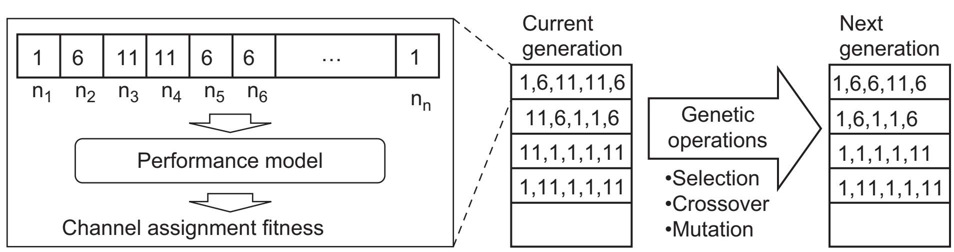


Fig. 7. Implementation of the WMN channel assignment algorithm.

using conversion functions

$$f\_\mathrm{dec} = \frac{\ln(x+e)}{\sqrt{x+1}}, \tag{5}$$

and $f\_inc(x) = 1 - f\_dec(x)$. Functions convert metrics into strictly monotonic values between zero and one as presented in Fig. 6. The f_{dec} function is used for decreasing metrics, such as cost, and f_{inc} is used with increasing ones.

The WMN fitness f is defined as a product

$$f = \prod m_i^{s_i}, \tag{6}$$

where m_i is the value of the metric i and s_i is the significance factor of the metric. Significance factors are added to weight metrics differently. All metrics m_i have only values between 0 and 1. Basically ${m_i}^{s_i}$ forms a function such as presented in Fig. 6. Using a high value for s_i implies that only solutions with high value of metric i will have high fitness. Similarly with a small value of s_i, only low metric value will decrease the fitness value and fitness mostly depends on other metrics. It is also possible to ignore any particular metric completely by setting $s_i = 0$.

To make this more intuitive for the designer, the value of s_i is derived from a percentage value p_i from 0 to 100. This is called significance value. When value p_i is greater or equal to 50, $s_i = (4 * p_i - 150)/50$. Otherwise $s_i = 50/(250 - 4 * p_i)$.

5. Algorithms for WMN deployment design

WMN deployment design optimization algorithms can be developed e.g. for channel assignment, topology optimization, and device parameter optimization. The first example algorithm, *WMN channel assignment algorithm*, shows that the performance model allows channel assignment with advanced routing metrics. *WMN pruning algorithm* shows how a simple algorithm can give powerful results when used with the performance model.

5.1. WMN channel assignment algorithm

The WMN channel assignment algorithm is genetic algorithm designed for static channel assignment. The target is to optimize existing network by selecting radio channels optimally. It is assumed that locations of APs have been designed by the network administrator to cover required areas. Each AP contains one or more wireless interfaces that may operate on allowed WLAN channels.

Genetic algorithms [20] have a pool of chromosomes that represent possible solutions. The number of chromosomes in the pool is the population size. Each solution implies some fitness that is calculated with a fitness function. With each iteration, a set of genetic operations can be applied. These include selection, crossover, and mutation. Operations use fitness

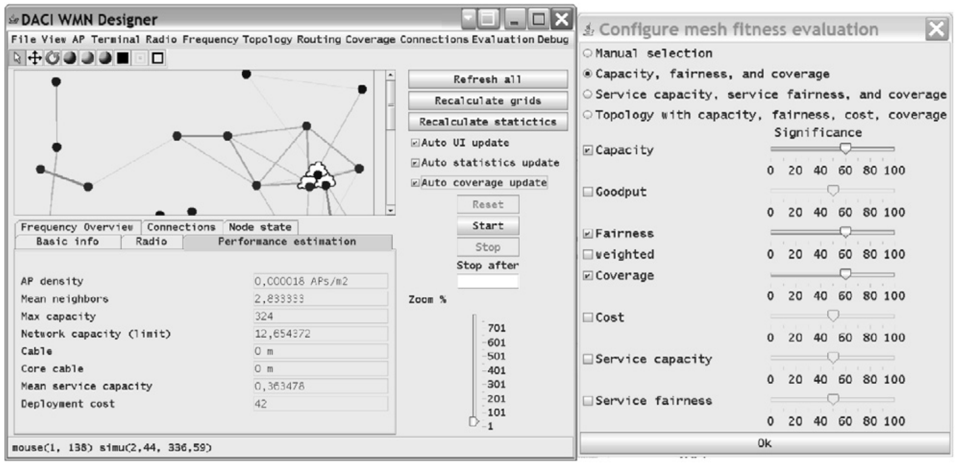


Fig. 8. Prototype GUI. The main view (left) and fitness configuration view (right).

function to evaluate the fitness of each solution and only solutions with high fitness are included in the next generation. This way, the population evolves toward the optimal solution.

Fig. 7 presents the implementation of the algorithm. A chromosome with n genes is used, where each gene represents a mesh point interface and its channel. Basically, channel is encoded as an integer with three allowed values. The performance model is used as a fitness function using the weights selected by the user.

5.2. *WMN pruning algorithm*

The WMN pruning algorithm checks the necessity of each mesh point based on the WMN fitness. The algorithm operation is very simple. First, the fitness calculation is configured according to user preferences and the algorithm calculates the initial fitness of the network. Then, the algorithm checks each mesh point in random order by calculating the WMN fitness with and without the particular mesh point. If fitness is higher without the mesh point, it is disabled. Otherwise the mesh point is left to the network. This method quickly removes mesh points that are not needed.

During the development, more advanced variations of the same idea were evaluated. For example, a pruning algorithm that selects APs that are removed using a specified order by removing APs with the highest negative effect on the fitness value first. However, it was found that the original version is much faster and still gives comparable results compared to the more advanced ones.

6. Prototype and simulation arrangements

A prototype tool named *WMN Designer* implements the performance model and optimization algorithms. The prototype is a development platform for WMN deployment methods and contains an interface to the NS-2 simulator [41] for simulation and result verification. The prototype aids algorithm development by enabling testing and evaluation, and network visualization.

Fig. 8 presents the main view and the fitness configuration view of the prototype Graphical User Interface (GUI). The main view shows a graphical visualization of the simulated network. Fitness calculation is configured according to user preferences with the fitness configuration view. GUI provides methods to set configuration for the network as well as methods to load and save network configurations.

The prototype supports detailed parameterization of the used equipment. Device radio parameters can be set globally, or optionally individual parameters can be set for each AP. These include WLAN adapter sensitivity, cables, and antenna gains for both omni- and directional antennas. The prototype supports multirate operation by defining receiver sensitivity levels for each transmission rate in WLAN adapter configuration.

Signal propagation and interference is estimated using a propagation model. Currently, the prototype implements three propagation models: FreeSpace, TwoRayGround, and Shadowing [41].

Routing algorithm and the used routing metrics can be freely selected. Current implementation uses the Floyd–Warshal algorithm with hop count, and Expected Transmission Time (ETT) [10] routing metrics. Hop count implements the basic shortest path routing. ETT is based on the transmission time of a packet using the particular link. Thus, it captures the affect of path length, and link capacity. ETT for a link l is calculated $ETT_l = ETX_l \frac{s}{b_l}$, where ETX_l is the expected number of MAC layer transmissions to successfully transmit the packet over the wireless link. The packet size is s, and link rate b_l [45].

6.1. *Implementation*

The prototype is implemented with Java and has an architecture presented in Fig. 9. All network objects, their relations, and current state is stored in the *WMN parameters*. The WMN parameters also contains the propagation model, radio

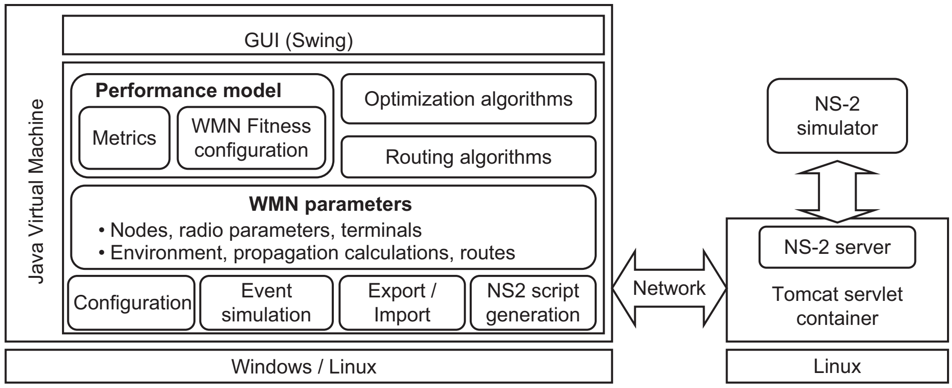


Fig. 9. Prototype architecture.

parameters, and up-to-date routing information. The *routing algorithms* block implements the used routing metrics and algorithms. It stores the generated routing information into WMN parameters. *Mesh metrics* are calculated based on WMN parameter information. This block implements the performance model metrics. The *WMN fitness configuration* implements the fitness function that can be configured by the user. Both WMN metrics and fitness can be used by the *optimization algorithms*. The implementation of channel assignment optimization algorithm uses Java based genetic algorithm implementation JGAP [22].

Additional blocks include *GUI*, *Configuration*, *Event simulation*, *Export and Import*, and *NS2 script generation*. The prototype is configured using an Extensible Markup Language (XML) configuration file that exists for propagation models, equipment parameters, and network planning preferences. The prototype also contains an event based simulator to model the operation of distributed algorithms in WMN. Export and import block allows the network configurations to be saved and loaded from the file system. Finally, the NS2 script generation implements functionality to create a NS-2 simulator TCL file and execute simulation according to the WMN described in the prototype [41]. NS-2 simulation is implemented using a Java servlet that provides an interface to the standard NS-2 simulator. This enables the verification of the prototype results with an external simulator.

7. Simulations

For evaluating metrics and the operation of the optimization algorithms, 24 simulation cases were executed. Used network topology presented in Fig. 10 contains six mesh portal APs and 30 non-portal APs in 1400 m × 1400 m area. Same topology was used across the simulations to keep the results comparable with each other. Locations of portal APs were selected manually to create two mesh portal installation sites that both contain three mesh portals. Because three channels were used, this allows each mesh portal in the same installation site to use non-interfering frequency in the optimum frequency assignment. Otherwise the topology is random but some mesh

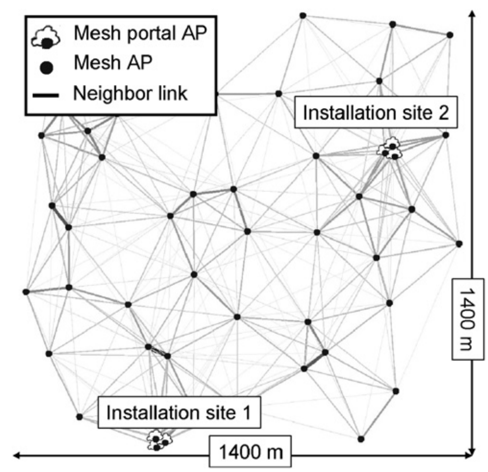


Fig. 10. WMN topology used in the simulations. Line thickness represents the link rate.

APs were moved to ensure that each AP has a possibility to have a route to a mesh portal.

Parameters of the devices were selected based on the specification of Cisco Aironet 1240AG Series 802.11G AP [7]. In multirate operation, the maximum bit rate is 54 Mbit/s with −73 dBm sensitivity. The device has 10 rate steps and the minimum sensitivity is −96 dBm. Interference sensitivity was selected to −99 dBm. In single rate simulations, 54 Mbit/s rate with −96 dBm minimum sensitivity was used.

In the simulations results, metrics are presented as percentage values. In addition to the metrics from the Section 4, mean route length and connectivity percentage are also presented to give further insight of the network topology. These values are not used in the optimization algorithms. Connectivity is the share of existing routes compared to all possible routes. Mean route length percentage is calculated by comparing mean route length to the maximum practical route length of the simulation topology. Each mesh portal has five APs in a column and the mean route length is 5.37. This notation was used simply to allow mean route length to be presented in the same chart as the metrics.

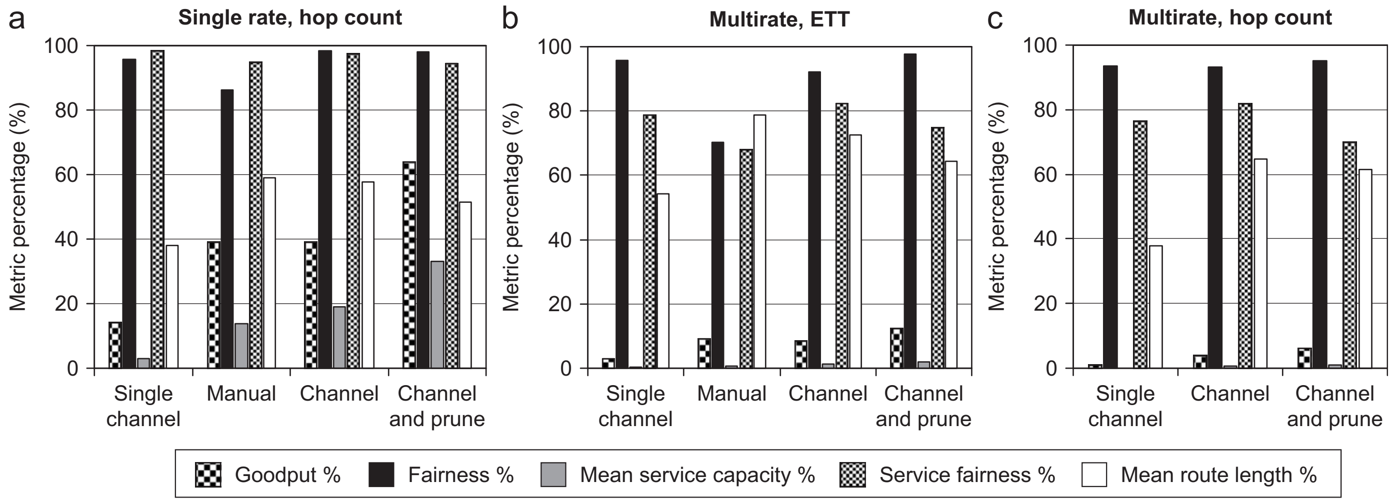


Fig. 11. Effect of WLAN multirate operation and routing metrics. (a) Hop count routing metric without multirate operation, (b) ETT with multirate, and (c) hop count metric with multirate.

Simulations are done using both the WMN channel assignment algorithm and the WMN pruning algorithm. To save simulation time, the WMN channel assignment algorithm was automatically halted if the fitness did not increase with the last 100 iterations. JGAP uses dynamic population size, i.e. it alters the population size from the initial size in order to get better results.

7.1. *Effect of multirate links and routing metrics*

The purpose of the first simulation set was to compare optimization methods and evaluate the effect of multirate operation and routing metrics on WMN deployment design. First, multirate operation was not used and the routing was done using hop count metrics. Therefore, the usage of ETT would not alter the results. The second and third case were done using multirate operation, the second one with ETT routing metric and the third with hop count. All simulations were run using capacity, AP fairness, and coverage metrics with equal significance values. The initial population size was 400 and the number of iterations was 400.

WMN design done manually with advanced understanding on WMN performance was added for a reference. A designer was allowed to change the channels and remove nodes but not alter the node positions. Possible neighbor and interfering nodes were known, as well as link rates. This requires signal propagation calculations but no performance model or optimization algorithms are needed. The strategy was to minimize the interference in the network, distribute mesh points equally for frequency channels, and minimize the route length from each mesh AP to the mesh portal.

Fig. 11 presents results for non-optimized (single channel), manually designed (manual), optimized with WMN channel assignment algorithm (Channel), and optimized with WMN channel assignment and pruning algorithms (Channel and prune) with different multirate and routing schemes. In non-optimized topology, all nodes use the same channel. Goodput metric is presented instead of WMN capacity because goodput can directly be presented with a percentage value. Their information content is the same because the number of mesh portal is constant in the simulation. Coverage was 100% in all cases.

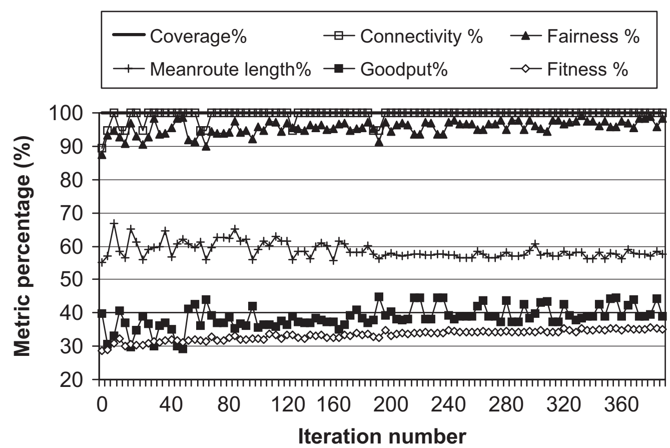


Fig. 12. Detailed view to metric values during the optimization process.

According to the results, both optimization algorithms outperformed the single channel and manual WMN design. Manual WMN design almost reached the capacity of the WMN channel assignment algorithm with the expense of decreased fairness. Multirate WMN is even more difficult for manual design as shown by the results.

Results also show that the use of multirate operation has a major effect on the network capacity. Also, the usage of hop count metric with multirate operation lowers the network capacity. This is because routes with lowest number of hops often contain long links with low link rate. The mean capacity increase in the simulations was 131% with the channel assignment optimization and 318% with both channel assignment optimization and pruning, compared to the capacity of the single

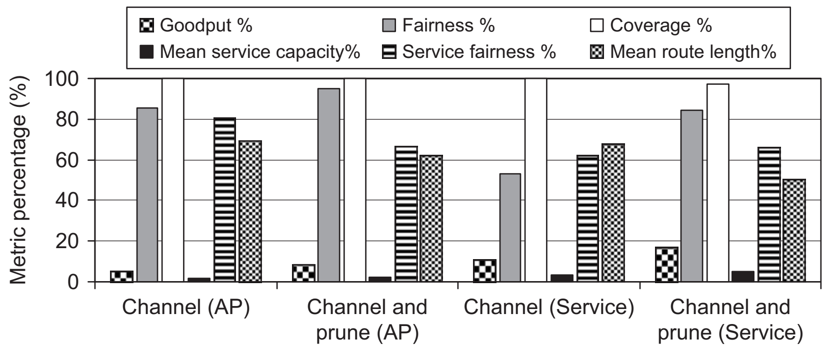


Fig. 13. Using service capacity and service fairness as optimization metrics.

channel topology. Still, both fairness and coverage were kept above 90% with all simulation cases. In multirate cases, the service fairness is significantly lower due to user unfairness caused by different user rates depending on the user location.

7.2. The genetic algorithm optimization process

Fig. 12 shows a detailed view to the optimization process of the previous section. Selected case represents the optimization of WMN with hop count routing and without multirate operation. It shows values for coverage, connectivity, fairness, mean route length, capacity, and fitness in percentages for every fourth iteration cycle. Fitness increases steadily through the whole optimization process, which suggests that the number of iterations could be even higher to reach better results. The graph also shows the importance of fairness. Fairness and capacity are competing with each other. Each time when the iteration result has high fairness, the capacity is, respectively, lower. Coverage is kept in 100% almost during the whole optimization process similarly than the connectivity. This implies that the network is fully connected. Significant insight is the fact that the mean route length decreases during the optimization. This is characteristic for optimization using hop count metrics without multirate operation. However, this is not necessarily the case with multirate operation and ETT.

7.3. Selecting optimization metrics

The second simulation set compares service capacity and service fairness metrics to the capacity and AP fairness metrics. The simulation uses multirate operation with ETT routing metric. Optimization is done using WMN channel assignment (Channel), and channel assignment and pruning (Channel and prune) algorithms. The initial genetic algorithm population size was 100 and the number of iterations was 100.

The results are presented in Fig. 13. Mean service capacity percentage is calculated by comparing the mean service capacity to the maximum link capacity that user terminal may have. Two bar sets in the left, Channel(AP) and Channel and prune(AP), are done using capacity, AP fairness, and coverage metrics with equal significance values. Results marked with Channel(Service), and Channel and prune(Service) are done using service capacity, service fairness, and coverage metrics with equal significance values. According to the results, when service capacity and fairness were used, the capacity of the network was significantly increased with the expense of fairness. Thus, service fairness is not adequate metric for optimization but AP fairness should be preferred.

In general, the service fairness can be high although the capacity distribution is unfair among APs. However, if distribution of AP locations is not uniform, using service fairness gives more weight to APs that require more capacity. With uniform distribution of AP locations, the AP fairness metric guarantees that service fairness is also taken care of.

7.4. Effect of metric significance values

Table 4 presents the effect of different coverage and fairness significance values compared to capacity significance. Simulation was done with capacity significance value of 50%. Each cell contains four values that are achieved capacity, fairness, and coverage percentages, as well as mean route length in the network. The simulation shows that without enforcing fairness the capacity of the network is high but APs are not treated fairly. Practically this means that APs that are not within a communication distance to a mesh portal are excluded from the topology. Enforcing fairness immediately affects the capacity whereas the effect of coverage is not high. This is partly explained by the fact that initial coverage is already quite high. However, if we use only coverage, fairness decreases significantly.

7.5. Evaluation with NS-2

Additional evaluations were done with the NS-2 simulator [41] using the IEEE 802.11b models. It contains implementation of 802.11b as well as other involved protocols. Parameters for the IEEE 802.11 MAC protocol were selected as follows. The Request-to-Send (RTS) and Clear-to-Send (CTS) messages were used. The transmission power used was 15 dBm. The number of retries for missing packets in the MAC level was 7. The propagation model in the simulation was TwoRayGround.

The simulation topology was the same as used in previous simulations. Since the maximum data rate was 11 Mbit/s, optimization and pruning were run again with the new parameters.

Table 4
Effect of different values of coverage (k) and fairness (j) significance

	$j = OFF$	$j = 50\%$	$j = 100\%$
$k = OFF$	69.6 | 12.1 | 97.0 | 2.6	8.0 | 89.1 | 100 | 4.2	5.7 | 94.9 | 100 | 3.7
$k = 50\%$	60.8 | 11.4 | 100 | 2.8	5.1 | 92.9 | 100 | 3.7	3.7 | 98.0 | 100 | 3.8
$k = 100\%$	58.1 | 10.8 | 100 | 2.7	6.9 | 90 | 100 | 3.7	5.1 | 93.7 | 100 | 4.2

Results are presented as (capacity % | fairness % | coverage % | mean route length).

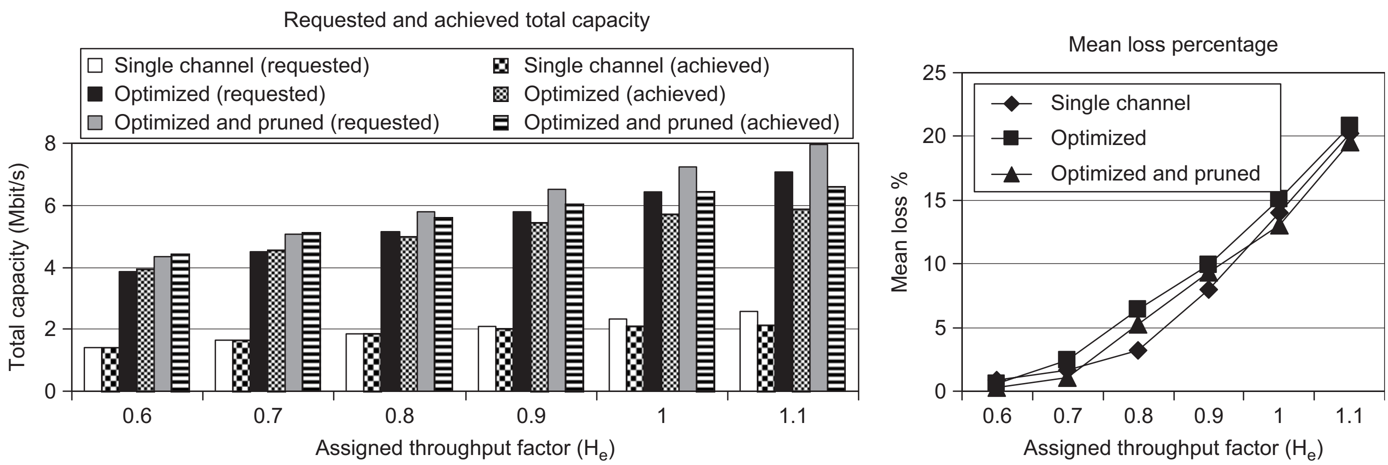


Fig. 14. NS-2 simulation results.

The optimization increased the capacity 2.75 times compared to the single channel setup. The result was almost exactly the same as with 54 Mbit/s rate presented in Fig. 11. The effect of pruning was slightly smaller.

Three terminals were created for each mesh AP and a bidirectional Constant Bit Rate (CBR) connection was created between each terminal and the closest mesh portal. The distance of each terminal and AP was 30 m. The packet size with each connection was 1500 bytes.

Bit rate for each terminal was selected according to the *capacity* value given by line 35 in the ESTIMATE-MESH-CAPACITY algorithm. The terminal bit rate $B_t(n)$ for a terminal associated with AP n was achieved by

$$B_{\mathrm{t}}(n) = H_e M_e \frac{capacity(n)}{n_{\mathrm{t}}}, \tag{7}$$

where $capacity(n)$ is provided by the ESTIMATE-MESH-CAPACITY algorithm, and n_{t} is number of terminals associated with AP n. From the nominal throughput of 11 Mbit/s, only about one third can be achieved in practice with RTS-CTS. The capacity of a single hop link was measured with NS-2 simulator and the result was 3 Mbit/s. Factor $M_e = 0.27$ represents this.

Fig. 14 presents both requested and achieved capacities from the NS-2 simulation. Terminal throughputs were modified by changing the H_e factor to evaluate the accuracy of the ESTIMATE-MESH-CAPACITY algorithm. With value $H_e = 0.8$, the achieved capacity started to decrease compared to the requested capacity, and the mean loss rate started to increase. There are two reasons why the achieved capacity in NS-2 simulation results is slightly worse than estimated with the performance model. The performance model takes into account all traffic from nodes inside the interference range. However in NS-2, nodes that are outside the communication range and inside the interference range cause collisions despite of the IEEE 802.11 RTS-CTS mechanism. Another reason is that the distance of traffic source and AP is zero in the performance model. When the distance of terminals is higher, they cause some interference to other mesh points. As a summary, the performance model estimates the *capacity* values well but small amount of capacity should be reserved to the IEEE 802.11 MAC inefficiency.

8. Conclusions

A performance model and two optimization algorithms for WMN deployment design are presented in this paper. The performance model contains seven metrics that were proven sufficient for WMN deployment optimization with multiple evaluation criteria. Metrics are combined into a configurable WMN fitness that is used to optimize WMN deployment according to user preferences. Developed performance model and algorithms have been implemented with a prototype. WLAN multirate operation and user defined routing metrics are supported by the presented methods. Simulation results show that the performance model gives valuable insight of the WMN topology and can be successfully used with the optimization algorithms. In the presented cases, the achieved capacity increase with the developed optimization algorithms compared to a single channel frequency assignment was between 230% and 470% without chancing the WMN topology. Furthermore, multirate operation and advanced routing metrics was found crucial in WMN deployment design. In future, the research will concentrate on the development of new algorithms utilizing the performance model.

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