On the Performance of Hybrid Wireless/Wired Mesh Networks

Sebastian Max, Lothar Stibor, Guido R. Hiertz
Chair of Communication Networks
Faculty 6, RWTH Aachen University, 52074 Aachen, Germany
{smx—lsr—grh}@comnets.rwth-aachen.de

Dee Denteneer Philips Research, HTC 27 (WL 1.132)
5656 AE Eindhoven, The Netherlands
dee.denteneer@philips.com

Abstract

Wireless Mesh Networks (WMNs) transparently extend the coverage of a portal via Mesh Points (MPs) which relay data over multiple hops to the associated stations. While this concept lowers costly wire installations, capacity is reduced by the multiple transmissions.

Therefore, multiple portals are needed to limit the route length, resulting in a wireless network supported by a wired backbone. In this paper, we analyze how the variation of the average ratio of MPs per portal effects the network performance. To do so, a realistic system model is defined which incorporates the typical characteristics of a wireless link based on IEEE 802.11a. Then, we use an analytical framework which allows to compute the capacity in an arbitrary network topology under the conditions of the system model.

The comparison of the average system capacity with different ratios shows that the performance gain diminishes with increasing number of portals: While the step from one to two portals doubles the capacity, there is only a small difference between 1 *and* 0.5 *MPs per portal. Furthermore, a simple cost model provides insights to the economical feasibility of WMNs: In the case that an MP costs about 10% of a portal, the optimal ratio is found to be around* 5 *MPs per portal.*

Keywords: Wireless Mesh Network, Hybrid Network, Capacity Analysis

1. Introduction

Since the standardization of IEEE 802.11 the number installed Wireless Local Area Networks (WLANs) grows exponentially. Based on simple, inexpensive technology and license-free bands, they allow for a convenient, wireless access to a wired network, usually the Internet. The fundamental element in 802.11 is the Basic Service Set (BSS): One or more Stations (STAs) associate to the stationary Access Point (AP), which is the portal to a wired backbone.

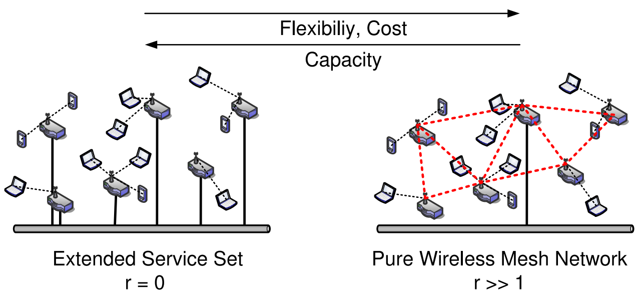

Figure 1: The coverage of IEEE 802.11 can be extended using a wired (ESS) or a wireless (mesh) backbone. The possible solution space in between is characterized by the ratio r of mesh points per portal.

Currently, IEEE 802.11 observes a trend which is common to many successful standards: It is used in scenarios for which it was initially never designed. One of the arising deployment concepts is the coverage of large areas with ubiquitous wireless Internet access. If the area covered by one AP does not suffice, a provider installs multiple APs which are interconnected by a wired backbone. The set of all APs together with the associated STAs is defined as the Extended Service Set (ESS), which is drafted in the left part of Figure 1.

In many cases the installation of the wired backbone represents the major cost-factor; hence, it seems promising to introduce Mesh Points (MPs): Instead being connected to the wired backbone directly, they forward data to or from the nearest portal, possibly over multiple wireless hops. From the viewpoint of the STAs they look like a regular AP; the relay-service is provided completely transparently. In the extreme, only one portal exists in the network; in this case, a pure Wireless Mesh Network (WMN) is formed, as given in the right part of Figure 1.

While this configuration results in minimal installation costs and maximal flexibility, its usefulness is restricted to small networks. Since any packet has to pass the central portal, it becomes the bottleneck of the network which has to be shared by all STAs. Therefore, in a network consisting of n STAs, the capacity per user is bounded by $O(1/n)$.

To get rid of this inherent bottleneck, multiple portals are installed which all directly connect to a wired backbone. Hence, the network becomes a hybrid wired/wireless mesh network. Its structure can characterized by the ratio r of MPs per portal. With r equal to 0, the backbone is purely wired (representing the ESS case), the pure WMN is given for very large values of r.

In this paper, we concentrate on the question how the network performance is affected by this ratio. This question is approached as follows: Section 1.1 overviews the existing literature on hybrid mesh networks and points out our contributions to this research field. Afterwards, the system model, which abstracts the capabilities of the radios and the network is introduced in Section 2. Based on this system model, a method for capacity analysis is given in Section 3, which allows for a systematic evaluation of the upper bound system capacity in Section 4. Finally, our work is concluded in Section 5.

1.1. Related Work

The evaluation of capacity limits for wireless communication networks is a popular research topic. One of the most cited papers in this area is the seminal paper by Gupta and Kumar [3], where they discuss the asymptotic capacity of random ad-hoc networks.

Since the publication, their results have been extended by different researchers who calculated the capacity bounds in other network types. [7] analyzes the ESS case, where a network of p portals is connected via wires and provides a supporting backbone for n STAs. They show that if p grows asymptotically faster than $\sqrt{n}$, the throughput capacity rises linearly with n, which provides an effective improvement over a pure ad-hoc network.

The work in [11] extends this work significantly: Although the general result also gives the relation that more than $\sqrt{n}$ access points are required for significant gains, the result is achieved in a more general framework which includes a realistic channel model instead of the simple protocol model used in [7].

Due to the chosen approach, [3], [7] and [11] have in common that they derive fundamental scaling laws that describe the theoretical capacity under the model assumptions. Hence, one must be careful to apply them to an arbitrary and small network instance with a given topology. Especially the variations under different number of nodes and the details of the hybrid wireless/wired mesh network are not modeled satisfactorily.

This disadvantage is addressed by several other researchers (e. g. [4], [6]) who concentrate on the calculation of capacity limits in a given instance of an ad-hoc network. In the case of pure WMNs, [5] shows that the capacity of each node decreases as $O(1/n)$, where n is again the number of nodes in the network. To reduce the complexity of the calculation, a simplified channel model is used. Essentially, this model defines a collision domain for each link, consisting of all links that interfere with the first one.

In the case of many networks (e. g. IEEE 802.11 and IEEE 802.16-based), this simplification neglects several major system attributes: First, interference is an additive property, e. g. there are many scenarios where a link can be active if one of two interferers is active, but not if both are active concurrently. Second, the standards enable the STAs to choose from a wide range of Modulation- and Coding Schemes (MCSs) for the transmission. Low-rate MCSs are much more robust against interference than MCS with many data bits per transmitted symbol. Hence, it is impossible to assume a constant 'collision domain' or an 'interference graph'.

1.2. Our Contributions

To our best knowledge, the only work for the computation of the throughput capacity in arbitrary network instances which takes into account additive interference and different MCS is presented in [12]. In the paper at hand, we extend their method and apply it to a wireless network model which includes a realistic channel behavior. In contrast to the work in the literature, this behavior is characterized by

- its stochastic nature, which includes a correlated log-normal shadowing loss,
- the Signal to Interference plus Noise Ratio (SINR) and Received Signal Strength (RSS) requirements of the different MCSs and
- the efficiency of the link depending on the selected MCS.

Using the algorithms presented in [12] in combination with our system model allows for a computation of the throughput capacity in a given hybrid wireless/wired mesh network. For each different setting of the ratio r, we evaluate the resulting capacity in a Monte-Carlo fashion. For each sample, a random shadowing is used which determines the efficient placement of the MPs and the portals. The results allow for a sound judgment of the relations between the capacity, the ratio r of MPs and portals and the number of STAs in small- to medium-sized hybrid wireless/wired mesh networks.

2. System Model

We consider a square area A which is covered with a mesh network using m Mesh Points (MPs). Each MP provides wireless Internet access to a subset of the n Stations (STAs) which are distributed randomly in the area.

2.1. Channel Model

The received signal quality of a transmission from node N_i to N_j is described by the wireless channel model. An important requirement of this model is the inclusion of the severe shadowing which can be found in the typical deployment scenarios for Wireless Mesh Networks (WMNs): In dense urban city centers, the direct signal path is often obstructed by buildings. Hence, we use a stochastic channel model suited for these environments. It is explained in detail in [9]; here, we restrict us to indicate the following features:

- A deterministic path loss which is inversely proportional to d^{γ}, where d denotes the distance between the nodes and γ is the attenuation exponent, with $\gamma = 3.5$.
- A log-Normal shadowing process with zero mean and a variance of 8 dB, including the spatial correlation properties suggested by [10] and [2].

Based on the conclusions drawn in [9], we use the frequency band provided by IEEE 802.11a (at 5.5 GHz) with a maximum allowed transmission power of 30 dBm.

An exemplary reception footprint of this channel model can be found in Figure 2. As it can be seen in this example, the node's transmission area is frayed and non-contiguous, which is a result of the shadowing. Hence, a static transmission range (or even an interference range) as often assumed in the literature cannot be defined.

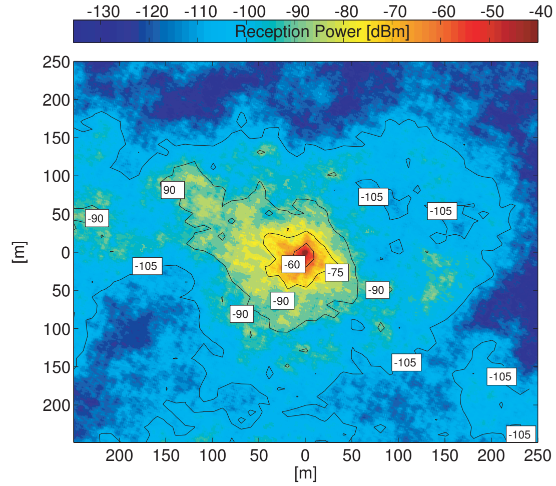

Figure 2: Reception power (in dBm) from a sender positioned at the center of the area.

To eliminate edge effects, we use a wrap-around technique: Given the border length b of the square area, the distance between two points (x, y) and (r, s) is calculated as

$$\sqrt{\min(|x-r|, b-|x-r|)^2 + \min(|y-s|, b-|y-s|)^2}. \tag{1}$$

In this way, the shortest path between the two points is not restricted to the direct connection, but is allowed to 'wrap around' the x- and/or the y-axis.

2.2. Physical Layer Model

The Physical Layer (PHY) model decides under which conditions a packet transmission is successful, i. e. the packet is decoded error-free at the receiver.

In our model, the success probability is calculated from two parameters: First, the Received Signal Strength (RSS), determined by the channel model, must be large enough to allow for a correct identification of the signal at the receiver. Second, if concurrent transmissions are active, the mutual interference plays an important role. This is modeled by the Signal to Interference plus Noise Ratio (SINR) as following: Let $\{N_t : t \in T\}$ be the set of transmitting nodes at a given instance. If now node $N_j, j \notin T$ receives from node $N_i, i \in T$, the SINR at N_j is

$$\mathrm{SINR}(N_i, N_j, T) = \frac{\mathrm{P}\left(N_i, N_j\right)}{Noise + \sum_{k \in T, k \neq i} \mathrm{P}\left(N_k, N_j\right)}. \tag{2}$$

For a successful packet transmission from N_i to N_j, a set of conditions have to be fulfilled.

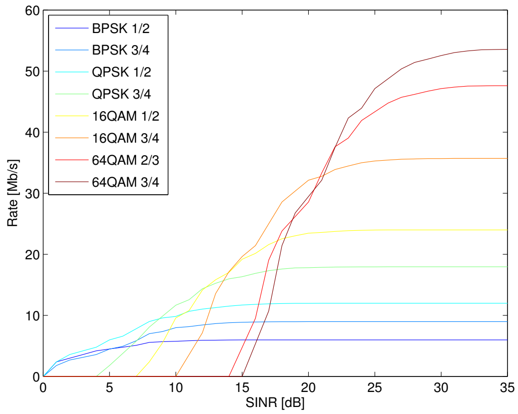

Figure 3: For a chosen Modulation- and Coding Scheme (MCS), the Signal to Interference plus Noise Ratio (SINR) determines the final transmission rate.

1. N_i must transmit only to node N_j, i. e. N_i cannot transmit and receive at the same time.
2. N_j must receive only from node N_i, i. e. N_j cannot receive and transmit at the same time.
3. The reception power $\mathrm{P}(N_i, N_j)$ must exceed a threshold $\mathrm{Thres}_{\mathrm{P}}\,(\mathrm{MCS})$.
4. The SINR must be high enough to allow a successful reception of the packet.

Conditions 3 and 4 are dependent on the Modulation- and Coding Scheme (MCS) which is selected by the transmitter. While the values for the $\mathrm{Thres}_{\mathrm{P}}\,(\mathrm{MCS})$ can be found in data sheets of available products (e. g. from [1]), the mapping of the SINR (together with the MCS) to the Packet Error Rate (PER) is provided in [8].

If all four conditions are fulfilled, the final transmission rate can be calculated; the resulting graphs for the possible MCSs is shown in Figure 3.

2.3. The Medium Access Control Model

While the PHY model abstracts the behavior of a single link, the Medium Access Control (MAC) model is responsible for the interaction of the entities in the network. Due to the nature of the wireless channel, transmissions have to be scheduled collision-free, which is performed using protocol overhead (e. g. idle times in IEEE 802.11) in the real implementation.

To estimate the maximum achievable throughput capacity, we assume an optimal MAC. This is modeled via an omniscient and omnipotent coordination entity, which

- has full knowledge about the PHY model for each link,
- controls the traffic load on each link, so that the end-to-end requirements are met,
- generates a schedule for the transmissions and
- disseminates this schedule to the nodes without costs.

All nodes operate under the guidance of this hypothetical controlling entity. This allows for an optimal schedule to be followed by the network, which maximizes the network capacity. How to find this optimal schedule under the restrictions and potentials of the system model is described in Section 3.

2.4. The Routing Model

Wireless mesh networks usually define a routing sublayer between the link layer and the network layer. Similar to the MAC model, we abstract the capability of the routing protocol and describe its effects on the traffic streams. While a STA simply connects to the MP with the highest Received Signal Strength (RSS), path selection among the MPs is driven by the end-to-end cost, measured in the total transmission duration. As it is already known from the PHY model whose links can operate using a given MCS, we can use the Floyd-Warshall algorithm to find the cheapest routes. This algorithm operates on a graph representation of the network topology, where all edges between the nodes are weighted with the maximum transmission rate.

2.5. The Network Topology Model

The capacity of a WMN heavily depends on the topology of the network. The presented stochastic shadowing model and the detailed physical layer model require a suitable topology: If it is not adapted to the current conditions, a connectivity of the mesh network cannot be guaranteed, which distorts the following capacity calculation. As an example, due to the irregular shape of the reception power, a regular grid or a hexagonal cell structure cannot be used.

This problem was analyzed in [9]. Here, a greedy algorithm is presented which positions the MPs in a given area such that the number of MPs is minimized, conditioned on a certain coverage and connectivity. For every shadowing instance, we apply this algorithm to generate a suitable topology, which provides a connected network with at least 95% area coverage.

The algorithm places only one portal in the mesh network, i. e. it generates only pure WMNs. Therefore, we enrich the network by placing wires between

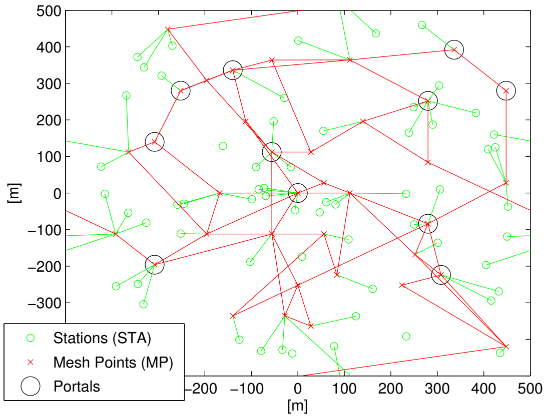

Figure 4: An exemplary instance of a mesh network with 11 portals, 24 MPs ($r \approx 2.2$) and 50 STAs.

selected MPs. To reduce the average number of hops in the most efficient way, this is done in an iterative way: First, with the help of the routing model, the route from each MP to the central MP is computed. Then, we count for each MP how many hops would be saved by placing a wire between it and the central MP, taking into account all routes. Finally, a new wire is placed such that the the MP with the highest number of saved hops is converted into a portal. This process is iterated until the required number of portals is reached.

An exemplary output of this routing can be seen in Figure 4. Beside the 11 portals and 24 MPs ($r \approx 2.2$), 50 STAs are positioned randomly into the area, which results in a network with an average hop count of 1.875 and a maximum hop count of 4. Using the method described below, the resulting uniform system capacity can be computed as 39.00 $^{\mathrm{Mb}}/_{\mathrm{s}}$.

2.6. Traffic Model

One of the typical properties which differentiate WMNs from Mobile Ad-Hoc Networkss (MANETs) are the traffic characteristics. While in MANETs it is assumed that potentially every node wants to communicate in a peer-to-peer fashion with every other node, the traffic in a WMN follows a different pattern: The major application is the provisioning of wireless Internet access; hence, all routes are either downlink from a portal to a STA or uplink with exchanged sources and sinks.

We model the Internet traffic by assigning each STA the same load, partitioned into 90% downlink traffic and 10% uplink traffic.

3. Capacity Calculation by Optimal Scheduling

The system model in Section 2 formulates the restrictions and potentials under which the nodes in the WMN have to operate. To find the capacity limit of the network under these constrains, we generate an optimal schedule for the network by the method explained in [12], which we summarize here shortly.

Time is divided into intervals of one s length; in each interval the same schedule is applied to align the transmissions which result in the delivery of the traffic to the destinations. A *schedule* is defined as a list $((\mathrm{S}_1, d_1)\,;(\mathrm{S}_2, d_2)\,;\ldots;(\mathrm{S}_s, d_s))$ of network states S and respective durations d; $\sum_{i=1\ldots s} d_i$ denotes the duration of the schedule. A *network state* represents a possible activity in the network by enumerating the active links including the transmitter, the receiver, the MCS and the source and destination of the packet.

A network state is *feasible* if each transmission is successful according to the PHY sublayer condition. A feasible schedule must contain feasible network states only; furthermore, it must fulfill all traffic requirements. Finally, a schedule is optimal if no other feasible schedule exists with a smaller duration.

The calculation of the optimal schedule is divided into two steps. In step one, the set of feasible network states is computed, denoted as $\mathcal{S}$. The second step converts this set to an instance of a Linear Programming (LP) problem, aiming at the minimum schedule length conditioned that all transmission demands given by the traffic model are fulfilled. The LP instance can be solved by applying an optimization toolbox, e. g. the one included in Matlab. The resulting output vector $\mathbf{d}^* = (d_1^*, \ldots, d_{|\mathcal{S}|}^*)$ assigns the durations to the network states. Having found the optimal schedule allows for computing the required radio resource utilization by summing up the durations of the network states.

The used traffic model assigns the same load l to each of the n STAs; therefore, the *uniform system capacity* $\mathcal{C}^u$ can be defined as

$$\mathcal{C}^u = \frac{l \cdot n}{\sum_{i=1\ldots s} d_i}. \quad (3)$$

Sometimes simply referred to as *system capacity*, it serves as a measure of performance for the mesh network.

3.1. Approximated Scheduling

With the usage of the described algorithm, the maximum number of nodes is restricted due to the computational complexity to 30 nodes. Although this provides ground for some experiments, it does not suffice for meaningful results. Therefore, heuristics are used to reduce the computation time.

The heuristic Selective Growing (SG) exploits the fact that only a small number of the generated Network States (NSs) contributes to the optimal solution: The set $\mathcal{S}$ is generated iteratively, starting with the NSs that contain only one active link. The optimal schedule for this limited set indicates which NSs are preferred, and only those are enriched with additional concurrent transmissions to create further NSs. This step is repeated until no new NSs can be created.

This method reduces the amount of NSs since only relevant NSs are used to generate new ones. Instead of increasing the set of NSs until no new ones can be found, the Early Cut (EC) heuristic monitors the reduction of the resource utilization with increasing number of concurrent transmissions. As soon as the relative reduction falls below a predefined threshold, the process is stopped and the last computed schedule is valued as a suitable approximation.

Monte-Carlo evaluations have been used to validate the performance of the approximation algorithms. For the network setups which are still computable by the exact scheduling, the relative error remains below 2%, which is smaller than the confidence intervals in the following evaluation.

4. Evaluation

In the evaluation, the set of feasible ratios $r = m/p$ is restricted by the limitation to integer values for the number of MPs m and portals p. Furthermore, the ranges of both values are constrained by size of the area A under consideration: the placement algorithm from the network topology model concludes with 45 nodes on average. Figure 5 indicates the values which are considered for the evaluation.

The evaluation of the impact of r is done with three different metrics. As a first approach, the average path length is used as an indicator for the system performance. After this initial survey, we perform Monte-Carlo simulations which are based on the system model and the optimization algorithm. This results in the mean upper bound capacity in hybrid wireless/wired mesh networks. Finally, we use a cost model to analyze the optimal ratio of MPs per portal from a combined cost- and capacity-perspective.

4.1. Average Route Length

The blue graph in Figure 6 shows how the average route length increases in the network with the number

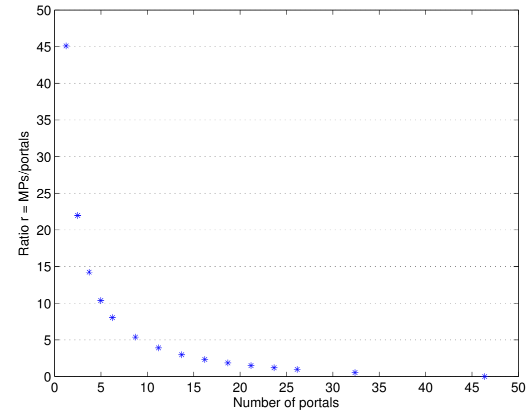

Figure 5: Parameter space for r.

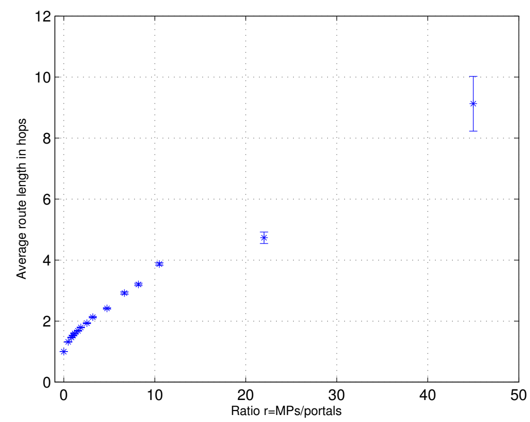

Figure 6: Average route length (in hops) for different ratios r.

of MPs per portal. Starting from nine hops for one portal and 45 MPs, which is not tolerable for a realistic installation, the average hop count is halved with the introduction of a second portal.

Of course, even with 4.5 hops on the average no capable usage can be expected. If an average of 3 hops or less is targeted, a ratio r of less than 10 MPs per portal is needed. A ratio of 4 assures an average hop count of 2, but then it gets much harder to push the ratio lower, as every added portal can only affect a low number of routes and thus has a minor impact on the network.

4.2. Average Uniform System Capacity

While the average route length only provides a rough indication of the performance of the WMN, the upper

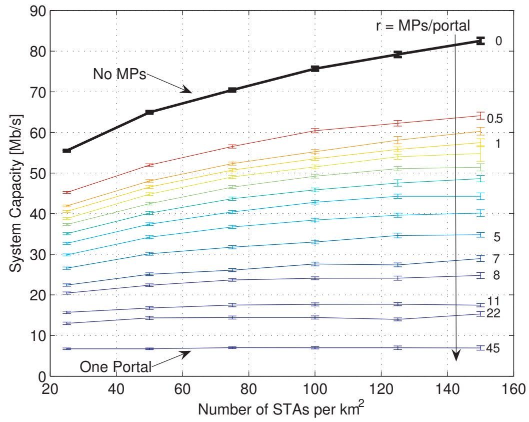

Figure 7: System capacity for different ratios r and number of served STAs.

boundary for the system capacity allows for a justified selection of the ratio r of MPs per portal.

For each considered ratio r of MPs per portal, several samples are needed to reduce the size of the confidence interval of the estimated mean capacity. For each sample the following process is required:

1. We generate a new instance of the shadowing process. Then, MPs are positioned and portals are selected according to the network topology model defined in Section 2.5 until the ratio r is reached.

2. Then, n STAs are distributed randomly; the induced traffic is determined as described by the traffic model in Section 2.6.

3. Using the routing model from Section 2.4, the routes from the STA to the portal and back are determined.

4. With the help of the optimization algorithm explained in Section 3, the required resource utilization is computed. Finally, the uniform system capacity for this network topology is derived from the resource utilization and the traffic load.

The iterative generation of samples results in the mean value of the uniform system capacity, $\overline{\mathcal{C}^u}$. To support the validity of the mean values, the size of its 95%-confidence interval is at most 5% of the value itself. Furthermore, the 95%-confidence intervals are indicated in the graphs.

For each ratio $r \in [0 \dots 45]$, the number of STAs per square kilometer is varied between 25 and 150. In Figure 7, the capacity gain which results from the increased number of portals becomes visible: While a network with one portal is limited to 7.5 Mb/s, the addition of another portal doubles the capacity. Of course, every further reduction of the number of MPs per portal increases the system capacity.

An interesting observation is made by the variation of the number of STAs: If only one portal exists, it is the bottleneck of the network and the capacity is independent from the number of STA. With each added portal, the effect of this bottleneck becomes smaller and the capacity becomes dependent on the STAs. This effect is explainable with the increased multiuser diversity which affects the number of possible options for the scheduling optimization. This result stands in contrast to [5] where a constant system capacity is concluded; this difference is rooted in the much simpler channel model from [5].

4.3. Cost Analysis

Wireless Mesh Network (WMN) are said to be cheaper than a purely wired network because installation and maintenance costs can be saved. This is based on the fact that one of the major cost factors during the deployment is the installation of wires to the portals. However, the system capacity is reduced if too few portals exist. Hence, we investigate the effects of different ratios to a combined capacity- and cost-metric.

We will use the following cost model: The sum of the capital- and operational expenditures for one portal is normalized to 1 \$; the sum of the expenditures for one MP is denoted as c_{MP} and ranges between 0.01 and 1\$. The *system capacity cost*, measured in Mb/s\$, is then defined as

$$\frac{\overline{\mathcal{C}^u}}{m \cdot c_{\mathrm{MP}} + p \cdot 1\$}, \tag{4}$$

where m denotes the number of MPs and p the number of portals. In contrast to the previous section, the number of STAs is fixed to 100 per square kilometer.

The system capacity cost expresses how much the additional capacity costs which is provided by decreasing the ratio of MPs per portal. For the evaluation, its value in a network where no MPs are used ($r = 0$) represents an economical hurdle which a WMN has to pass to be efficient.

For the system model under consideration, this hurdle is slightly above 1.6 Mb/s\$ (75.6 Mb/s divided by 46\$). In Figure 8 it can be seen in the left part of the graph, which is of course independent from c_{MP}. The remaining area shows how the introduction of MPs affects this measure: It is possible to identify four different regions, depending on the MP cost ranging from 0.01 to 1\$:

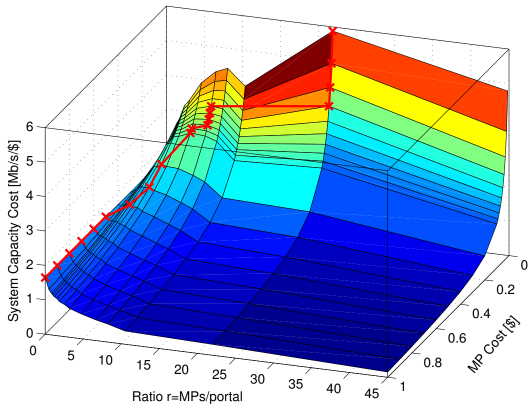

Figure 8: System capacity cost; the cost of a portal is normalized to 1$. The maximum system capacity cost for each MP value is given by the red line.

- **below 0.05$:** If the MP cost is very low, a very high ratio of more than 20 MPs per portal is favorable, allowing a system capacity cost of up to 6 Mb/s$.
- **0.05 to 0.2$:** With a reasonable low MP cost, the advisable number of MPs per portal can be found at 4 to 6, which results in a system capacity cost around 3 Mb/s$.
- **0.2 to 0.4$:** With increasing MP cost, the advantage of the hybrid WMN becomes less significant. To maximize the system capacity cost, a small number of MPs per portals (i. e. 2-3) can be used; however, their gain is low.
- **above 0.4$:** If $c_{\mathrm{MP}} > 0.4\$$, the maximum system capacity cost using a hybrid WMN is below a network consisting of portals only.

5. Conclusion

Using the system model and the optimization framework, we are able to show that the variation of the ratio of MPs per portal has a significant impact on the uniform system capacity. While the step from one to two portals halves route length and doubles the capacity, the benefit of adding more portals portals to the network diminishes if many portals are already active.

The cost analysis shows that if the expenditures for an MP are at most 40% of a portal, the installation of MPs becomes advantageous from an economical viewpoint. Often, the major cost factor is the installation of the wires to the portal; therefore, this value should be undercut in most deployments. If the MP cost amount to 10% of a portal, the optimal system capacity cost can be found using around 5 MPs per portal.

It can be concluded that the concept of hybrid wireless/wired mesh networks is able to exceed the capacity/cost ratio of a traditional cellular network if deployed in downtown/urban areas, especially if the cable installations account for the main expenditures.

References

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

[2] X. Cai and G. B. Giannakis. A two-dimensional channel simulation model for shadowing processes. *IEEE Transactions on Vehicular Technology*, 52(6):1558–1567, Nov. 2003.

[3] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, 2000.

[4] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu. Impact of interference on multi-hop wireless network performance. *Wireless Netwoks*, 11(4):471–487, July 2005.

[5] J. Jun and M. L. Sichitiu. The nominal capacity of wireless mesh networks. *Wireless Communications*, 10(5):8–14, Oct. 2003.

[6] V. S. A. Kumar, M. V. Marathe, S. Parthasarathy, and A. Srinivasan. Algorithmic aspects of capacity in wireless networks. In *Proc. of the ACM SIGMETRICS Conference*, pages 133–144, Banff, Canada, June 2005.

[7] B. Liu, Z. Liu, and D. Towsley. On the capacity of hybrid wireless networks. In *Proc. of the IEEE Conference on Computer Communications (INFOCOM)*, Mar. 2003.

[8] S. Mangold, S. Choi, and N. Esseling. An Error Model for Radio Transmissions of Wireless LANs at 5GHz. In *Proc. Aachen Symposium 2001*, Aachen, Sept. 2001.

[9] S. Max, L. Stibor, G. Hiertz, and D. Denteneer. Ieee 802.11s mesh network deployment concepts -invited paper-. In *Proc. of European Wireless Conference 2007*, page 7, Paris, France, Apr. 2007.

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

[11] S. Toumpis. Capacity bounds for three classes of wireless networks: Asymmetric, cluster and hybrid. In *Proc. of the 5th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc)*, pages 133–144, Roppongi, Japan, May 2004.

[12] S. Toumpis and A. J. Goldsmith. Capacity regions for wireless ad hoc networks. *IEEE Transactions on Wireless Communications*, 2(4):736–748, July 2003.