A Benchmark for Channel Assignment Algorithms in Wireless Testbeds

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***Abstract*—Channel assignment for multi-radio wireless mesh networks has been proven efficient to increase the network performance by decreasing the interference of simultaneous transmissions. Many algorithms have already been proposed, however, a meaningful comparison of their performance is difficult. The main reasons are that different experimentation environments and performance metrics are used for their evaluation. Thus, finding a universal methodology for the performance evaluation that ensures comparability is complicated. In this paper, we close this gap with a methodology for the performance evaluation of channel assignment algorithms in wireless testbeds. We developed domain-specific performance metrics that express the decrease of network-wide interference. Using these metrics, we developed benchmarking scenarios for performance measurements in wireless testbeds. We present the benchmarking results of a distributed link-based channel assignment algorithm and compare the results to a random-based algorithm and a single channel network. The evaluation was run on the DES-Testbed, a 128 node multi-radio testbed at the Freie Universität Berlin.**

***Keywords*-channel assignment; performance evaluation; benchmarking; multi-hop testbed; wireless mesh network;**

I. Motivation

Channel assignment for multi-radio *wireless mesh networks* (WMNs) attempts to increase the network performance by decreasing the interference of simultaneous transmissions. The reduction of interference is achieved by exploiting the availability of fully or partially non-overlapping channels. Using non-overlapping channels for otherwise interfering transmissions, increases the load the network can carry and thus enables better support for data-intensive applications such as video streaming. Channel assignment can be applied to all wireless networks based on technologies that provide such non-overlapping or orthogonal channels. Examples of widespread technologies are IEEE 802.11a/b/g, IEEE 802.11n, and IEEE 802.16 (WiMAX).

Although channel assignment is still a young research area, many different approaches have already been developed [1]. The approaches differ not only in the way channels are assigned to the network nodes (or more specific to the network interfaces), but also in the assumptions on the used network and interference models. The same applies to the performance evaluation of the algorithms because different performance metrics, some directly related to the employed interference model, are used. One example is the *fractional network interference* (FNI) metric [2] which is feasible for algorithms that model the interference with a *conflict graph* [3] and gives an insight of the performance in terms of interference reduction according to the used interference model. However, the results are only comparable to algorithms that also model the interference with a conflict graph.

Another challenge for the comparability of the performance is that the algorithms are evaluated in different experimentation environments, comprising analytical analysis, simulation studies, and experiments in real network deployments such as wireless testbeds. Recently, experimentation in wireless testbeds has gained in importance, since often-used simplified heuristics for modeling interference, such as the *m-hop interference model* [4], have been proven to be not very accurate for real network deployments [5], [6]. However, performance measurements on different testbeds can not be compared without taking the features of the particular testbeds into account. For instance, the testbeds may differ in number of nodes, number of network interfaces per node and the number of available orthogonal channels.

The contribution of this paper is a holistic methodology for the performance evaluation of channel assignment algorithms in wireless testbeds. We developed performance metrics in respect to the domain-specific goal to reduce interference. Based on these metrics, we developed a benchmark suite that can be used in order to measure the performance of a wide range of channel assignment algorithms. We present the performance measurements for a link-based distributed channel assignment algorithm on the Distributed, Embedded Systems-Testbed (DES-Testbed) comprising 128 multi-radio nodes. The developed performance metrics and the benchmark suite is not limited to this particular testbed and can be applied easily to other existing systems.

The remainder of the paper is structured as follows. An overview of performance evaluation methodologies for channel assignment algorithms is given in Section II. The developed performance metrics and the benchmark is presented in Section III, the performance evaluation follows in Section V. The paper concludes with an outlook on future work.

II. State of the Art

Three different sources of interference can affect the network performance of wireless mesh networks as depicted in Figure 1. *Intra-path* interference occurs when multiple nodes on the path of a single flow utilize an overlapping channel and if they reside in each others interference radius. Especially single channel networks are prone to this kind of interference. *Inter-path* interference results when two links of different flows interfere with each other. As a third source, *external* interference results when devices, which are not under control of the network operator, utilize the same frequency band. Channel assignment algorithms usually try to reduce inter- and intra-path interference and leave external interference aside, since it can not be controlled. However, due to the increasing number of WMN deployments, awareness towards external interference is receiving more attention [7].

In distributed approaches, each node calculates its channel assignment based on local information. Distributed approaches can react faster to topology changes due to node failures or mobility and usually introduce less protocol overhead, since communication with a central entity, usually referred to as *channel assignment server* (CAS), is not necessary. As a result, distributed approaches are more suitable once the network is operational and running. A main trade-off exists between the channel-diverse assignment and the network connectivity, since only interfaces that are tuned to the same channel can communicate with each other. One solution is to switch a dedicated interface to a common global channel to preserve the network connectivity [8]. Link-based channel approaches preserve the network topology by assigning channels to links instead of interfaces [2], [9], thus being transparent to the routing layer. Another solution is to have one interface per node on a fixed channel for receiving and dynamically switch to the channel of the receivers fixed interface for sending [10]. The *Skeleton Assisted Partition Free* (SAFE) algorithm uses *minimal spanning trees* to preserve the connectivity [11].

For the evaluation of these algorithms different performance metrics have been developed. These metrics can be classified into metrics that measure the *decrease of interference* and those that measure the *increase of network performance*. The former metrics are used to measure the decrease of interference achieved by the particular algorithm according to the used interference model. Usually, the overall network interference is measured after the application of the channel assignment algorithm and compared to a single channel network or random channel assignment [9]. While it is a good approach to take the cause of the problem into account, it has to be kept in mind that the interference model is a simplification of the complex interference effects in reality. Therefore, an evaluation in an experimental environment is necessary to validate the performance results under realistic conditions.

The latter metrics address this problem by analyzing the performance of the algorithms indirectly by measuring the network performance. The network performance is usually expressed using throughput-based metrics, since increasing the network capacity is the main goal. In order to measure the network capacity, the network saturation has been used as performance metric in [2], [8]. Measurements of the achievable throughput on random multi-hop paths have been performed in [10], [11]. The packet loss rate has been measured in [12]. The variety of used performance metrics makes it hard to compare the performance results of the algorithms. We propose a holistic benchmark for the performance evaluation of channel assignment algorithms in wireless testbeds in the next section.

III. Channel Assignment Benchmark (CAB)

The *channel assignment benchmark* (CAB) comprises metrics and scenarios to measure the performance of channel assignment algorithms in wireless testbeds. Benchmarking is a well known method in computer science for the performance evaluation of a *system under test* (SUT) [13], [14]. The performance score of a SUT can be compared intuitively with the numbers scored by other systems. In the channel assignment domain, the SUT comprises the particular channel assignment algorithm and the wireless testbed on which the performance evaluation is carried out on.

Often used metrics for expressing the network performance are based on measurements of the achievable throughput and end-to-end delay. Considering channel assignment algorithms, metrics are of particular interest that express the performance in regard to the reduction of inter-path and intra-path interference effects. We present two performance metrics to assess the reduction of interference based on sequential and simultaneous throughput measurements of possible interfering links. Additionally, the network saturation is a feasible indicator of the increased network capacity. Finally, it is also interesting to consider the introduced protocol overhead in form of exchanged control messages. As next, we describe the performance metrics and how they can be measured.

A. Intra-path Interference Ratio (IAR)

The throughput of a multi-hop data flow may be reduced due to the impact of intra-path interference. Let $p_{u,v}$ be the m-hop path, with $m > 2$, from node u to node v. Let L be the set of all links on $p_{u,v}$. In order to measure the impact of the intra-path interference on $p_{u,v}$, we perform the following two measurement steps. First, we measure the achievable throughput t_l^{seq} on each link $l \in L$ sequentially, meaning only one link is active at a time. The aggregate throughput over all measurements expresses the maximum throughput that is available on this path in an interference-free environment and can be written as $T_{seq} = \sum_{l \in L} t_l^{seq}$. As next, we measure the throughput of all links in $l \in L$ simultaneously. The aggregate throughput over all measurements expresses the maximum throughput that is available on this path when all links are activated at the same time and thus exert the highest interference on each other. It can be written as $T_{sim} = \sum_{l \in L} t_l^{sim}$.

The *Intra Path Interference Ratio* (IAR) metric is then defined as the ratio of the two aggregated throughput measurements with

$$IAR = \frac{T_{seq}}{T_{sim}} \tag{1}$$

A value for IAR close to 1 means that the aggregate throughput is not reduced when the throughput is measured on all links on $p_{u,v}$ simultaneously. In this case, the algorithm

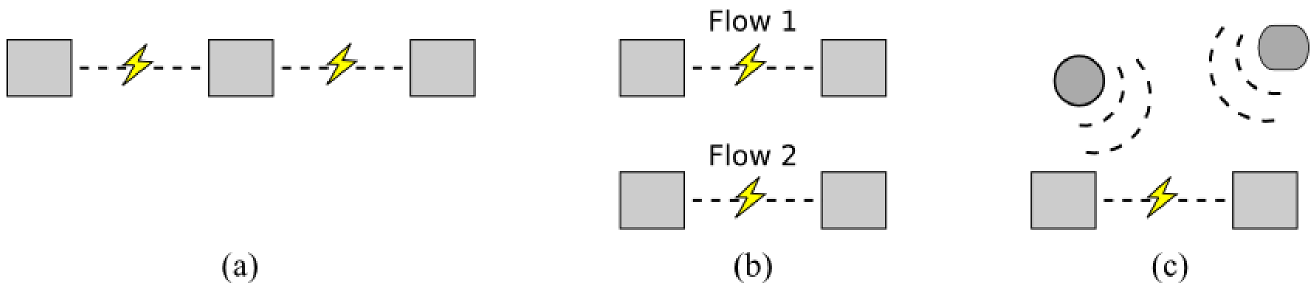

Figure 1. Intra-path, inter-path, and external interferences. (a) Intra-path interference may occur when two hops on a path utilize the same channel. (b) Inter-path interference results when two hops of two different flows interfere with each other. (c) External interference is exerted form devices which are not under control by the network operator.

was capable to reduce the intra-path interference with the calculated channel assignment. A lower value for IAR expresses a higher impact of intra-path interference on $p_{u,v}$.

Breaking the path down and measuring the capacity of each link on its own has the advantage to avoid bottleneck effects. Otherwise, if we start a data flow from node u to node v over $p_{u,v}$, the throughput on each link is limited by the throughput of the predecessor link. By considering each link on its own, we avoid the effect of such bottleneck links.

B. Inter-Path Interference Ratio (IRR)

To measure the effect of inter-path interference, we select a subset L of all wireless links in the network with the additional constraint that every network node can only be adjacent to one link $l \in L$. This way, no multi-hop path is possible considering only the links in L. The links in L shall be in close physical proximity as their effect on each others' data transmission is subject of this measurement. As for the previous metric, we first measure the achievable throughput t_l^{seq} on each link $l \in L$ sequentially, the aggregate throughput over all links is $T_{seq} = \sum_{l \in L} t_l^{seq}$. In a second step, we activate all links simultaneously and measure the aggregate throughput which is $T_{sim} = \sum_{l \in L} t_l^{sim}$.

The *Inter-Path Interference Ratio* (IRR) metric is then defined as the ratio between the aggregated throughput of sequential transmissions and concurrent transmissions.

$$IRR = \frac{T_{seq}}{T_{sim}} \tag{2}$$

The concurrent transmissions will exert a maximum interference, whereas the sequential transmissions express the achievable throughput in an environment free of inter-path interference. Since each network node is participating in at most one traffic flow, we measure the throughput reduction caused by inter-path interference. A value for IRR close to 1 means that the aggregate throughput is not reduced when all links are activated simultaneously. Thus, the algorithm is capable to reduce the inter-path interference with the calculated channel assignment. A lower value for IRR expresses that there is a higher impact of inter-path interference by multiple data flows.

C. Saturation Throughput Ratio (STR)

The *saturation throughput* is described as the maximum load that the system can carry in stable conditions [15]. It can be determined by increasing the traffic load on the system until the limit is reached. This metric can be used to directly show an increase of the network capacity gained with a channel assignment algorithm.

For the measurement procedure, we define L as the set of all wireless links in the network. In the first iteration $i = 0$, we take a subset of k links $S_{i=0} \subseteq L$ with $|S_{i=0}| = k$ and the constraint that each node can only be adjacent to one link $l \in S_{i=0}$. We then measure the aggregate throughput of all links in $S_{i=0}$ simultaneously which is $SAT_{i=0} = \sum_{l \in S_{i=0}} t_l$. For the next iteration $i = 1$, we add another random k links with the same constraints and repeat the measurement. The procedure terminates if $SAT_{i+1} \leq SAT_i$ or S_i cannot be extended any further. In other words the total aggregate throughput of the network will no longer grow or it is impossible to generate any new single hop data flows. The network is now saturated. Therefore we define the saturation throughput S as follows:

$$S = \max_{\forall i}(SAT_i) \tag{3}$$

In this way, we measure the absolute values for the saturation throughput and therefore, it is specific to the testbed and lacks interoperability. To solve this, we set the saturation throughput achieved by a channel assignment algorithm S_{CA} in relation to the saturation throughput of a single channel assignment S_{Single}. In other words, S_{CA} will be normalized using a single channel assignment as a baseline and expresses how much the saturation throughput has increased over a single channel network.

As performance metric, we use the *saturation throughput ratio* (STR) as follows

$$STR = \frac{S_{CA}}{S_{Single}} \tag{4}$$

A value of STR greater than one indicates an increase in the network capacity due to the channel assignment, i.e., STR = 2 means that the network capacity has been doubled compared to the single channel network. A value of STR close to 1 indicates that the algorithm has almost no impact on the network capacity.

D. Protocol Overhead (PO)

The overhead of the protocol is the additional amount of control messages the channel assignment approach poses on the network. The control messages are exchanged between nodes, either on a regular basis, on demand, or during a set up phase. They are used for example to negotiate channel switches or to inform the neighboring nodes of changes in the channel assignment. As those control messages use the same communication paths as application data, they consume resources that would have been otherwise available to the latter. Consequently, the protocol overhead does affect negatively the goodput of the network. Thus it is desirable, that channel assignment approaches have a minimum protocol overhead.

A metric for protocol overhead has to factor in the mere amount of such control messages, the amount of nodes involved in exchanging those messages, and how often those messages will be exchanged. As performance metric, we define the *protocol overhead* (PO) as the mean number of messages sent by each node with

$$PO = \frac{1}{|N|} \cdot \sum_{u \in N} m_u \tag{5}$$

where N denotes the network nodes and m_u is the number of protocol messages sent by node u.

IV. Benchmark Scenarios

With the described performance metrics, the benchmark consists of the following five steps

1) *Network initialization:* All testbed nodes and the configuration of the wireless interfaces are reset.
2) *Channel assignment algorithm:* The channel assignment is started. When all instances of the algorithm terminate with the final assignment on all nodes, the performance measurements can start. The instances of the algorithms keep track of the sent protocol messages for later evaluation of the PO metric.
3) *IAR:* A random path of length 5 is selected using the *weighted cumulative expected transmission time* (WCETT) routing metric [16], which favors channel divers paths over single channel paths. We then measure the IAR as described above.
4) *IRR:* We select a subset of 10 wireless links which meet the constraint of the close spatial proximity. We then measure the IRR as described above.
5) *STR:* In a first step, we randomly select 10 wireless links and measure the aggregate throughput. For the next iteration we add another 10 links and measure the throughput again and repeat this procedure until the network is saturated.

For all measurements standard networking tools, such as `iperf` for throughput measurements, can be used.

V. Evaluation

A. DES-Testbed

All experiments in this paper were carried out on the DES-Testbed at the Freie Universität Berlin [17], [18]. The DES-Testbed comprises 128 multi-radio indoor and outdoor nodes and is deployed in an unshielded environment over the computer science faculty buildings. The indoor nodes are placed in an irregular topology in office rooms and lecture halls. A snapshot of the network topology is depicted in Figure 2. Each network node is equipped with three IEEE 802.11a/b/g radios. All experiments described in this paper use two Mini PCI cards with an Atheros AR5413 chipset running the `ath5k` drivers and a Ralink RT2501 USB stick.

The channel assignment algorithms in this study have been implemented based on DES-Chan, a framework for experimentally-driven research on distributed channel assignment in real network environments [19]. DES-Chan introduces an abstraction layer for operating system specifics and thus enables the researcher to spend most development time on the algorithm logic instead of, for instance, memory management and handling the wireless interfaces. The framework provides basic services and data structures that are often required for typical tasks in channel assignment algorithms. These services are *interface management*, *neighborhood-discovery*, *node communication*, and *interference models*. DES-Chan is available at the website of the DES-Testbed http://www.des-testbed.net.

B. Algorithms

We evaluate the *distributed greedy algorithm* (DGA) [2], which has been implemented based on DES-Chan [20]. DGA assigns channels to links and is therefore topology preserving, meaning that all links are sustained during the channel assignment procedure. A conflict graph is used to formulate the problem so that the number of edges in the conflict graph shall be minimized. Each wireless link between two nodes is owned by the node with the higher node ID and only this node may assign a channel to the link.

At the network initialization, all links are assigned to the same channel. Each node then iterates over all owned links and changes the channel of the link which results in the largest decrease of interference in the local neighborhood. The largest decrease is achieved with the combination of link u and channel k that removes most edges in the local conflict graph. The interface constraint is respected, which means that no more channels can be assigned to a node than it has interfaces. In order to avoid oscillation, each vertex and channel combination can only be changed once. Channel switches are carried out using a 3-way handshake and update information message for the interference set. A detailed description of DGA and the implementation candidate based on DES-Chan is available in [20].

Additionally, a *random-based channel assignment* (RAND) has been implemented. With RAND, one network interface on each node is set to a common global channel. The remaining interfaces are set to random channels. The single channel network, later referred to as SINGLE, utilizes only one interface on each network node which is tuned to a common global channel

C. Benchmark execution

For each algorithm, we replicated the benchmark 30 times. One execution lasted about 90 minutes in average, depending

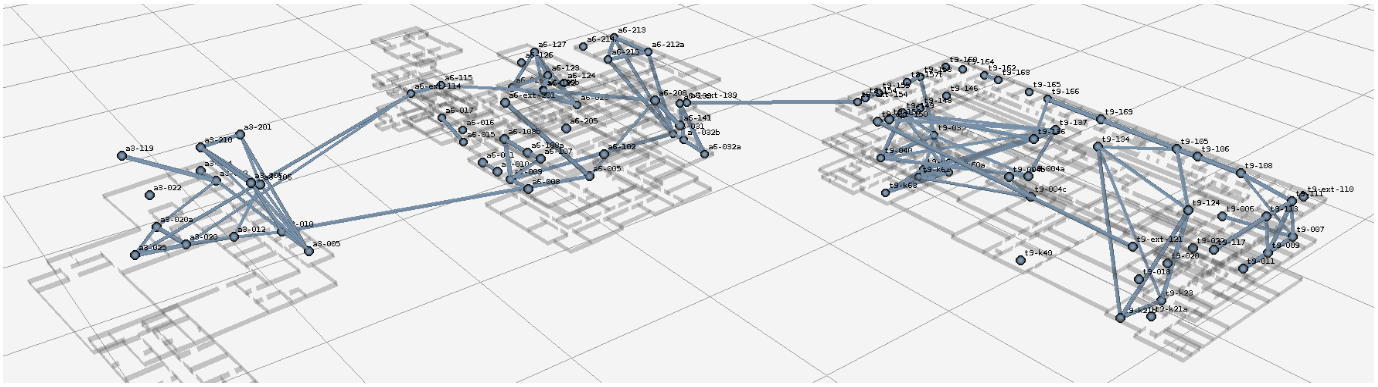

Figure 2. Network topology of the DES-Testbed. The 128 multi-radio mesh routers are deployed over 3 buildings in the computer science faculty.

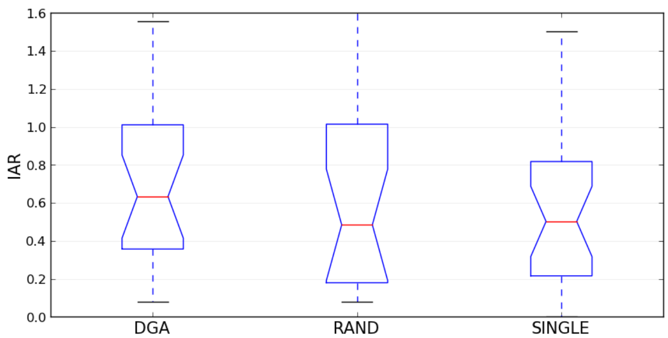

Figure 3. Results for the intra-path interference Ratio (IAR) scenario. The results show that DGA achieves the highest reduction of intra-path interferences. For the single channel case, the effect of intra-path interference is most severe.

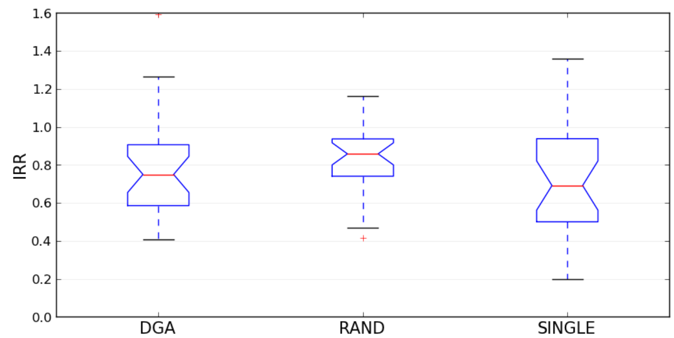

Figure 4. Results for the inter-path interference Ratio (IRR) scenario. Both algorithms DGA and RAND are capable to reduce the inter-path interference. For the single channel case, only 60% in the median of the aggregated throughput could be preserved, when the links are activated simultaneously.

on the particular channel assignment algorithm. This lead to a total runtime of 45 hours for all experiments in this study.

D. Results

The results for the IAR performance metric are depicted in Figure 3. DGA performs best with an median IAR score of 0.65, which means that 65% of the aggregated throughput could be preserved when the links on a multi-hop path are activated simultaneously. In comparison, the random channel assignment RAND achieves a median of only 0.5 and performs therefore only slightly better than the the single channel case. This shows that intra-path interference has a severe effect on the performance, only 50% of the aggregated throughput could be preserved when the links are activated simultaneously in a single channel network.

The results for the IRR performance metric are depicted in Figure 4. The RAND algorithms shows the best results with a median of 0.83 for IRR. DGA performs slightly worse with a median of 0.78. Both algorithms were able to preserve about 80% of the throughput that could be achieved in an environment free of inter-path interference. As expected for the single channel assignment, IRR is the lowest with 0.63 in the median.

The results for the saturation throughput ratio (STR) are depicted in Figure 5. For both algorithms DGA and RAND and

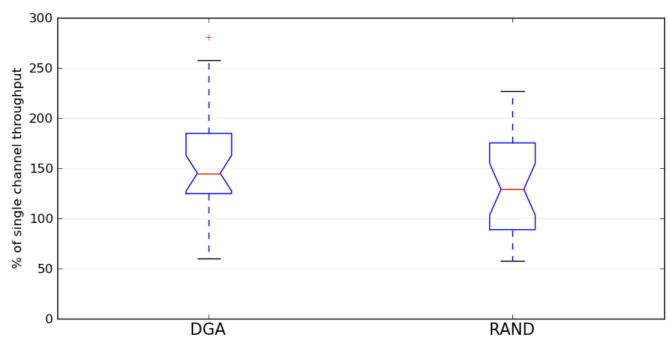

Figure 5. Results for the network saturation ratio (STR). The results show that DGA achieved a 48% increase of the network capacity compared to the single channel network case. RAND achieved a 30% increase.

their respective topologies it has been possible to extract up to 60 node disjoint wireless links. Compared to the saturated throughput in a single channel network, DGA was able to increase the throughput by 48% percent in the median. RAND achieved an increase of 30%. The results for STR show that distributed channel assignment algorithms are an efficient tool to increase the network capacity.

Only the DGA algorithm can be evaluated in regard to the introduced protocol overhead, since RAND and SINGLE do not send any control messages. With DGA, the mean number

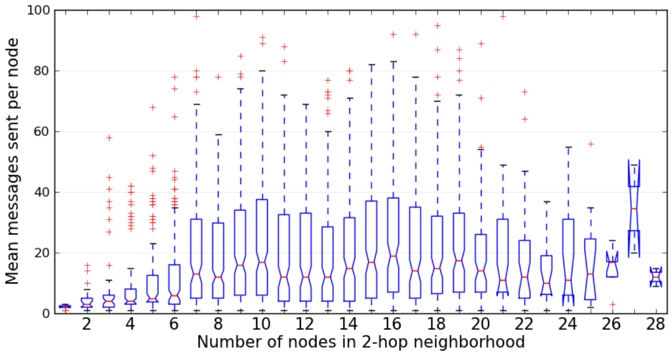

Figure 6. Protocol overhead of DGA. The plot shows the number of sent messages per node in relation to the number of nodes in the 2-hop neighborhood.

of sent messages over all benchmark runs is 18 per node. The number of sent messages per node in relation to the number of nodes in the 2-hop neighborhood is shown in Figure 6. The protocol overhead scales very well, the mean amount of messages sent increases slightly with an increasing size of the 2-hop neighborhood. The reason for the low protocol overhead is that only the nodes incident with the link in question negotiate the channel. Other approaches require that all neighboring nodes to acknowledge a pending channel switching operation which results in more sent messages [8].

The benchmarking results show, that the performance metrics and scenarios are feasible for the performance evaluation of channel assignment algorithms in wireless testbeds. The reduction of intra- and inter-path interference can be measured with the developed performance metrics and the results compared to a random channel assignment and the single channel network match our assumptions.

VI. Summary and Outlook

We presented a methodology for the performance evaluation of channel assignment algorithms in form of a benchmark suite for wireless testbeds. We developed domain-specific performance metrics that express the decrease of network-wide interference. For the evaluation of the performance evluation methodology, we evaluate a distributed link-based channel assignment algorithm (DGA), and compare the results to a random-based approach and a single channel network as a baseline on the DES-Testbed.

In future work, we will develop further algorithms for distributed channel assignment based on DES-Chan. The evaluation using the channel assignment benchmark (CAB) will enable a simple performance comparison of a wide range of different approaches. Additionally, we will further extend the benchmark suite with a scenario that measures the performance in regard to external sources of interference. Since interference of external devices will be more common due to an increasing number of wireless devices in the unlicensed frequency bands, channel assignment approaches are required to consider sources of external interference to maximize the network capacity

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