Self-organized Topology Construction and Channel Allocation for Multi-IEEE 802.16-2004 Radio Routers in Disaster Recovery

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Abstract. Self-organizing wireless metropolitan area networks connecting portable GSM/UMTS base stations are a valuable asset to rescue forces in disaster recovery. These networks can be formed by routers employing multiple commercially available IEEE 802.16-2004 interfaces. In this paper, we present and evaluate an algorithm for self-organized topology construction and channel allocation. The algorithm suggests (i) to estimate the capacity of potential wireless links from the measured signal-to-noise ratio, (ii) to run a modified Dijkstra algorithm to select links for topology construction in a way that maximizes network capacity and (iii) to greedily allocate channels to minimize interference. We evaluate our algorithm by simulations using QualNet. With the settings preferred by our industry partner, we find that 12 routers per square kilometer are sufficient to enable coverage. Trading path qualities and traffic load on gateways to the wired network significantly improves performance.

1 Introduction

In disaster recovery voice communication for rescue teams is a primary concern. Unfortunately, it is precisely in this situation that one cannot rely on public telephony infrastructure. A solution to this problem is to deploy routers with IEEE 802.16 technology to set up a wireless metropolitan area network (MAN) to connect portable GSM/UMTS base stations. In these scenarios IEEE 802.16 is of particular interest due to the guaranteed quality of service and the wide communication range. However, todays available IEEE 802.16-2004 technology has been designed as last mile technology and can only make up a single cell. Our industry partner thus currently builds routers with multiple IEEE 802.16-2004 interfaces that can be used to form wireless MANs that enable to connect GSM/UMTS base stations (see fig. 1 for an illustration). In base station (BS) mode, a 802.16 interface opens up a cell and offers connectivity for other routers to connect. In subscriber station (SS) mode, the interface can join a cell and connect the router to the network. Our work focuses on the case where each router comprises two IEEE 802.16-2004 interfaces.

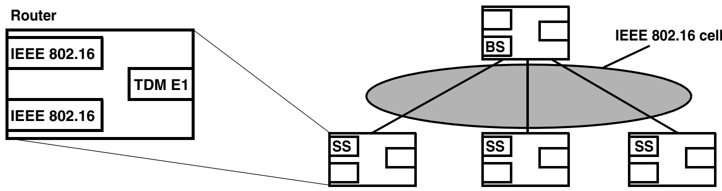


Fig. 1. A IEEE 802.16 cell that connects four routers. The router on top has one of its interfaces configured to base station (BS) mode. This router opens up a cell and offers connectivity. The routers on the bottom have configured one of their IEEE 802.16 interfaces to subscriber station (SS) mode to join that cell.

In this paper, we present and evaluate a distributed algorithm that enables routers to automatically form a multi-hop network in a self-organized way. It is well known that wireless interference severely limits network capacity in such multi-hop settings [1]. The algorithm thus determines

(i) how to construct the network topology, i.e. (ia) which routers need to switch an interface to base station mode and (ib) which wireless links are selected to interconnect the routers, and
(ii) which radio channels are allocated to the base station interfaces.

This link selection and channel allocation is performed in a way that optimizes the capacities on the path between the routers and gateways to the wired network to enable connecting GSM/UMTS base stations.

1.1 Application Scenario

The envisioned application scenario comprises around 40 wireless mesh routers dispersed over a metropolitan area of about 10 km^2. Around 15% of these routers are gateways that connect the wireless network to an infrastructure network. The traffic in the application scenario is packetized circuit-switched telephony traffic which has stringent quality of service requirements. The network is to be provisioned for the worst case. Hence, the traffic volume to connect a GSM/UMTS base station to a router is 2 MBit/s from the router up to a gateway and 2 MBit/s from the gateway down to the router (see [3] and [4] for details).

1.2 The Algorithm

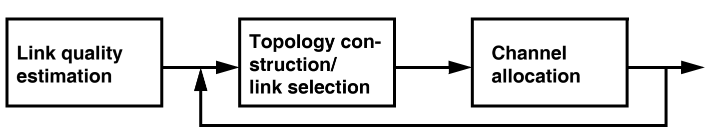


Fig. 2. Our algorithm to construct the network is incremental and subsequently involves link quality estimation, link selection and channel allocation.

Our algorithm for dual topology construction and channel allocation is inspired by a divide and conquer strategy to reduce the complexity. The overall concept is as follows (see fig. 2).

(i) Elect or configure one of the gateways in the scenario as a master gateway.
(ii) Start at this master gateway and subsequently invite the routers (including other gateways) to join and form the network.
(iii) To determine which router to join next, we propose to measure signal-to-noise ratios (SNRs) on all potential links that could be chosen in the topology construction and map these measurements to link qualities.
(iv) Based on the estimated link qualities, we infer path qualities to the gateways and employ a modified Dijkstra best path algorithm to incrementally decide which router to join next to form the network.
(v) If this join requires switching on a base station interface, we employ a greedy strategy to allocate a radio channel to the interface.

We justify this algorithm design with a review of graph theory. We then evaluate the algorithm with excessive QualNet simulations. With the settings preferred by our industry partner (25mW transmission power, 12 orthogonal channels of 10MHz width in the 5.8 GHz band), we find that 12 routers per square kilometer are usually sufficient to enable coverage. Moderately accounting for load on gateways by modifying the path quality metric, significantly improves overall network performance. We now head towards implementing the algorithm in a distributed environment before porting it into our industry partner's routers.

The rest of the report is structured as follows: Section 2 reviews link and path quality estimation. Section 3 reviews topology construction. Section 4 reviews channel allocation. Section 5 discusses evaluation results. Section 6 reviews related work. Section 7 concludes with a discussion.

2 Link and Path Quality Estimation

Table 1. Relation between SNR, modulation and coding scheme and link capacity on layer 2 as implemented in the Qualnet 4.0 simulator. The MAC layer capacities are derived from the physical layer capacities assuming a 25% overhead, a bandwidth of 10 MHz and a cyclic prefix (CP) value of 1/16.

Minimal Receiver SNR [dB]	Modulation and coding scheme	Capacity [Mbit/s]
6.0	QPSK 1/2	5.7
9.0	QPSK 3/4	8.5
11.5	16QAM 1/2	11.3
15.0	16QAM 3/4	17.0
19.0	64QAM 2/3	22.7
21.0	64QAM 3/4	25.5

It is a known fact [2] that modulation and coding scheme and thus the link capacity are derived from MAC layer SNR measurements (see table 1 for the relation). We thus propose to use the relative link capacity, i.e. the ratio between link capacity and maximal link capacity, as a link quality estimate when selecting links to construct the network topology. The link quality estimate can be expressed by a ramp function (see fig. 3) as an approximation or by a step function derived from table 1.

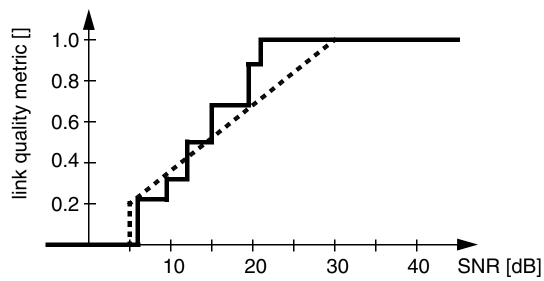


Fig. 3. The choice of modulation and coding schemes based on minimal receiver SNR can be employed to infer link quality estimates between 0 and 1. 0 stands for no capacity and 1 stands for maximal capacity.

We propose to compute the path quality metric *pqm* for the modified Dijkstra algorithm as described in table 2. The reasoning behind employing the product

Table 2. Link and path quality metrics investigated

Metric Name(No.)	Path Quality	Link Quality
pqm1 (1)	Product of link qualities	Ramp function in fig. 3
pqm2 (2)	Minimum of link qualities	Step function in fig. 3
pqm3 (3)	Product of link qualities	Step function in fig. 3

to derive the path quality from the link quality estimates on the path is that packet delivery ratios are multiplicative under the assumption of independence of packet loss. The reasoning behind employing the minimum is simply that the path capacity is determined by the capacity on the bottleneck link. We evaluate the three metrics in section 5.

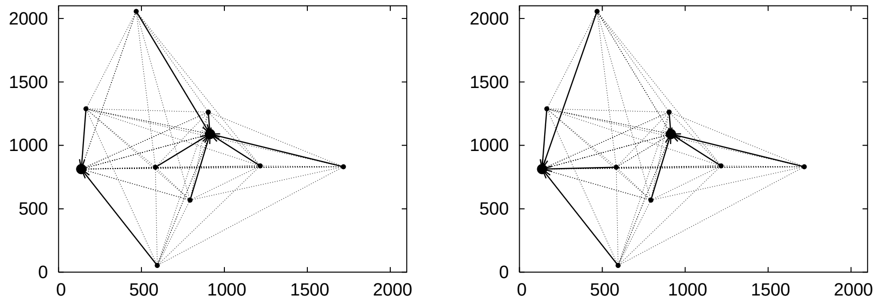
We further propose a *composite path metric* that accounts for the fact that the modified Dijkstra algorithm can cause a traffic overload at particular gateways. This composite path metric balances between the path capacity or quality and the traffic load already present on each of the gateways. Formally, we propose to define the path metric *cpm* based on path quality *pqm* and traffic load *tlm* by

$$cpm = w * pqm + (1 - w) * tlm \quad \text{with} \quad 0 \leq w \leq 1 \tag{1}$$

w close to 0 puts the focus of the composite metric on load balancing, and w close to 1 puts the focus on path qualities (see fig. 4 for an example). We define the traffic load part *tlm* of the composite metric by

$$tlm = \frac{GWcapacity - numAlreadyAssignedRouters}{GWcapacity} \tag{2}$$

where GWcapacity is fixed.



(a) w=1.0

(b) w=0.8

Fig. 4. Illustration of the effect of balancing load between gateways. The solid lines mark topology links and the thin dashed lines show potential connectivity. Left: No load balancing results in overloading of the gateway in the center. Right: Minimally accounting for gateway load during topology construction when computing the composite path metric leads to a more balanced topology (w=0.8).

3 Topology Construction

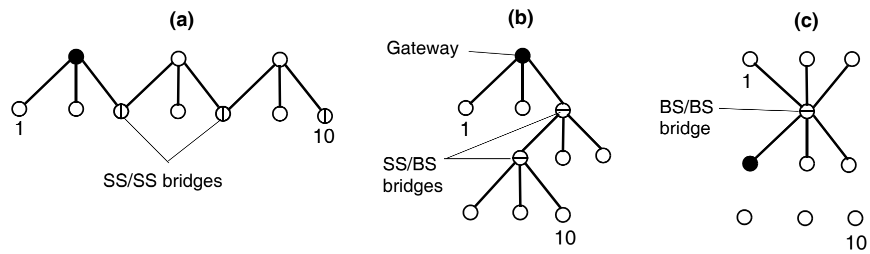


Fig. 5. Connecting 802.16 cells to build a multihop wireless mesh network using different types of bridges. A bridge connects two 802.16 cells by switching on both radio interfaces. The example illustrates three different ways to connect 10 routers when each cell is limited to a maximum of three subscribers. Figure (a) employs SS/SS bridges and needs 6 hops to connect router 1 and 10. Figure (b) uses BS/SS bridges and needs 4 hops to connect router 1 and 10. Finally figure (c) is not able to connect router 1 and 10 by using BS/BS bridges only.

Constructing the topology requires bridging between IEEE 802.16 cells. Bridging can be achieved with SS/SS, BS/BS, or SS/BS interface configurations on a router (see fig. 5). The stringent quality-of-service requirements for telephony circuit emulation makes bridging with a SS/SS configuration unfavorable. A BS/BS configuration is not favorable since this configuration implies that other bridges use a SS/SS configuration (see fig. 5). We thus restrict to uniform SS/BS configurations for bridges throughout the network. Gateways to the wired network have a BS/BS configuration to increase capacity. Leaf routers restrict to using a single interface with SS configuration to get connected. The other interface remains unused since redundancy is of no use when connecting outage sensitive GSM/UMTS base stations.

With these assumptions, the topology construction problem can be mapped to a connected dominating set problem[3]. In theory, this problem has been widely studied and has known solutions which we adopt to our problem. In mapping

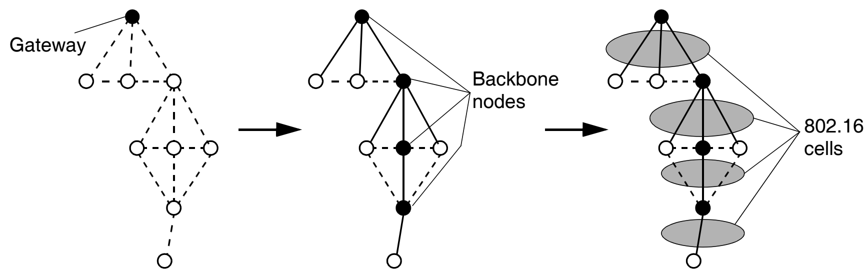


Fig. 6. Example for the mapping of a topology construction problem to a connected dominating set problem in graph theory. Selecting an interconnected set of backbone routers (black) that need to switch on their base station interfaces can be mapped to computing a connected dominating set in a graph.

our problem to graph theory the mesh routers correspond to vertices. Potential wireless links correspond to edges and link quality estimates correspond to the weights of these edges. The set of routers that are SS/BS bridges and thus need to configure their second interface to BS mode to open up a new cell then corresponds to a connected dominating set in the graph (see fig. 6). We call these SS/BS bridges backbone routers. The problem of selecting a set of backbone routers in a way that maximizes capacity on the paths from all routers to a gateway can then be mapped to maximizing path qualities in a graph while constructing the dominating set. However, it is known [11] that this problem can be solved with a modified distributed Dijkstra algorithm similar to the one employed in Open Shortest Path First (OSPF) routing.

3.1 Modified Dijkstra Algorithm

The logical intuition behind the modified Dijkstra algorithm is a wave front that starts at the gateway and separates vertices that are already part of the network from vertices that are not part yet. Vertices subsequently join one after another as the wave front proceeds. The sequence of joins is given by the path quality which can be inferred from the weights on the edges of the graph that represent the link quality estimates. Joining vertices need a parent vertex behind the wave front. Upon join, the parent vertex becomes a member of the connected dominating set if it has not been in this set already. The parent thus corresponds to a backbone router. The edge to the parent corresponds to a backbone link

[3] In graph theory, a graph consists of vertices and edges. A connected dominating set of a graph consists of the vertices of a dominating set of the graph plus a number of vertices that are needed to interconnect the vertices in the dominating set. A dominating set is a subset of the graph's vertices that has all remaining vertices adjacent to at least one vertex in the set.

in the network. Multiple gateways can be handled by the algorithm by selecting one master gateway and modeling the wired connection between the gateways as a link with optimal capacity/quality.

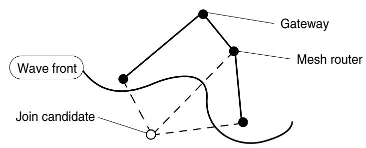


Fig. 7. Illustration of a join. The black circles mark routers which are part of the network and are hence behind the wave front. The white circle marks a router which is a join candidate, i.e. could be connected to the network along one of the dashed links. The modified Dijkstra algorithm then selects the candidate with the best path and the link that is associated with the best path. This candidate joins next and the wave front is advanced.

4 Channel Allocation

To perform channel allocation of backbone routers' IEEE 802.16-2004 interfaces in BS mode, we propose to employ a greedy strategy. We combine this strategy with the modified Dijkstra algorithm for topology construction and incrementally allocate channels as the wave front moves to join routers to the network.

We justify this algorithm design with the fact that the problem of assigning the k available channels to the IEEE 802.16 interfaces in BS mode can be mapped to a known graph coloring problem, namely to computing a max-k-cut to an interference graph. In this interference graph each vertex represents an IEEE

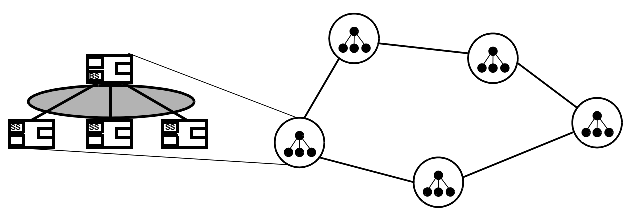


Fig. 8. Interference conflict graph for IEEE 802.16 cells in the network. Each vertex in the graph represents an entire cell in the network. Each edge represents a potential interference conflict between the vertices at its ends. This conflict arises when the cells represented by the vertices at both ends are assigned to the same channel.

802.16 cell in the network topology. The color of the vertex represents the channel assignment to this cell. Each edge represents a potential interference conflict between assignments. The conflict arises when the cells represented by vertices at the two ends of the edge are assigned to the same channel. The conflict diminishes when the channel assignments differ. Thus, the problem of finding an optimal channel assignment with k available channels can be mapped to the problem of coloring this conflict graph with k colors in a way that maximizes the number of conflict edges that have vertices with different colors at both ends. This problem is known as the max-k-cut problem [12].

The max-k-cut problem is known to be NP-hard [12]. Thus, it is not feasible to compute the optimal solution for non-trivial scenarios. However, there are a number of approximation algorithms that show good performance in both average and worst case [12]. These approximation algorithms include greedy, merge, genetic, and tabu-search. In this paper, we focus on the greedy algorithm, that assigns the k available channels in a round-robin manner since this algorithm can be easily combined with incremental topology construction. Since we have 12 channels in a network of at most 40 routers, this very practical choice presumably leads to a good performance unless the router placement is extremely dense.

5 Evaluation

We have implemented the proposed topology construction and channel allocation algorithm in QualNet. Using this implementation, we have conducted network simulations to evaluate its performance. We investigated (i) the coverage, (ii) the selection of path metrics, (iii) the trade off between path quality and gateway load and (iv) the behavior in a semi-static scenario, when routers join and leave the network.

5.1 Simulation Settings

The IEEE 802.16 interfaces of the wireless mesh routers are configured to one of 12 orthogonal channels which work at 5.8 GHz and have a bandwidth of 10 MHz. Transmit power is set to 25 mW. Antennas are omnidirectional, have a gain of 2 dBi and a height of 5 m. Receivers have a noise factor of 5.0. Routers are placed randomly over an area of 1400 m x 1400 m, 2100 m x 2100 m or 2800 m x 2800 m in a way that each router has at least one peer router in its connectivity range. Circuit-switched traffic is simulated as a pair of 2 Mbps constant bit rate (CBR) streams between each mesh router and a gateway. We run the simulation for 100 s. We repeat each run twenty times with different randomly generated router placements.

5.2 Coverage

Reviewing the results of our simulations, we have found that the density of the router placement in the scenario has to be above 12 per square kilometer (see fig. 9). This density is necessary to ensure a packet delivery ratio that is so close to one that circuit emulation traffic can be supported on at least 97% of the links (see fig. 9). In this case, the maximum packet delay from router to gateway is always smaller than 2 ms and packet jitter is smaller than 5 ms which is well below the requirements in the envisioned application scenario. Practically, the density of more than 12 routers per square kilometer is only achieved in the 1400 m x 1400 m scenario size given a total number of around 40 wireless mesh routers. We thus focus the rest of our evaluation on this scenario size.

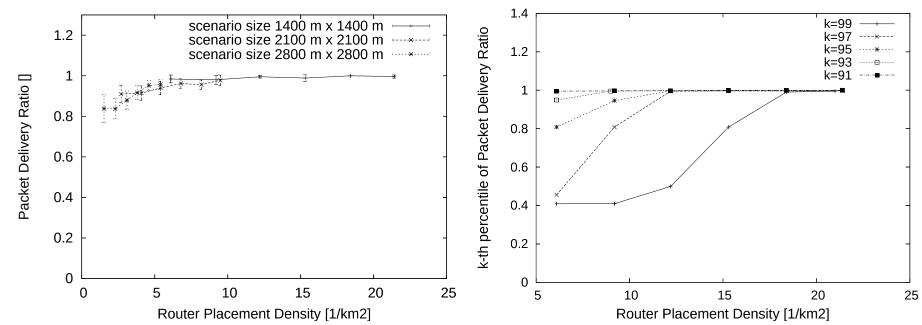


Fig. 9. Packet delivery rate at various router placement densities. The figure on the left side shows the simulation results for the three different scenario sizes.The figure on the right shows the minimum packet delivery rate obtained on k% (k=91, 93, 95, 97, 99) of the links. A reasonable PDR can only be achieved when more than 12 routers are placed per square kilometer.

5.3 Selecting Path Metrics

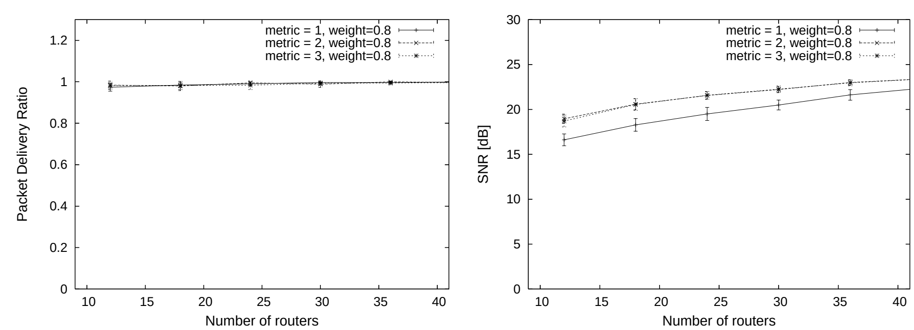


Fig. 10. Packet delivery ratio and SNR of the all-greedy algorithm with three different path quality metrics. The figure on the right shows that metrics $pqm2$ and $pqm3$ always lead to better average SNRs compared to metric $pqm1$. However, this better SNR does not necessarily lead to a better packet delivery ratio.

Investigating how the choice of path quality metric (see table 2) impacts performance, we find that this choice has little impact on the packet delivery ratio (see fig. 10). In terms of SNR, metric $pqm2$ and $pqm3$ outperform metric $pqm1$ (see fig. 10). This finding can be explained with the fact that a ramp function is an inaccurate approximation to model the SNR to link capacity relationship.

5.4 Trade off between Path Quality and Gateway Load

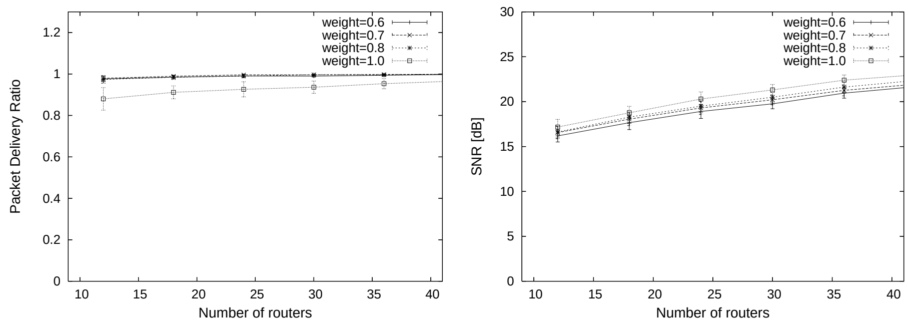


Fig. 11. Trading path quality versus gateway load increases the packet delivery rate.

Next, we investigate the trade off between path quality and gateway load. Figure 11 shows that accounting for gateway load significantly improves the packet delivery ratio. We note that trading path qualities and traffic load on gateways to the wired network is a prerequisite to meet the stringent quality of service requirements of telephony circuit emulation. However, the details of the choice of the trade-off parameter w in equation 1 is not significant as long as w is between 0.6 and 0.9.

5.5 Churn (Joins and Leaves of Routers)

Finally, we investigate the performance of the algorithm under churn. We consider three cases: (i) three mesh routers join the network all at a time, (ii) three mesh routers subsequently join the network, (iii) one mesh router leaves the network. Comparing the resulting packet delivery ratio and SNR to the values

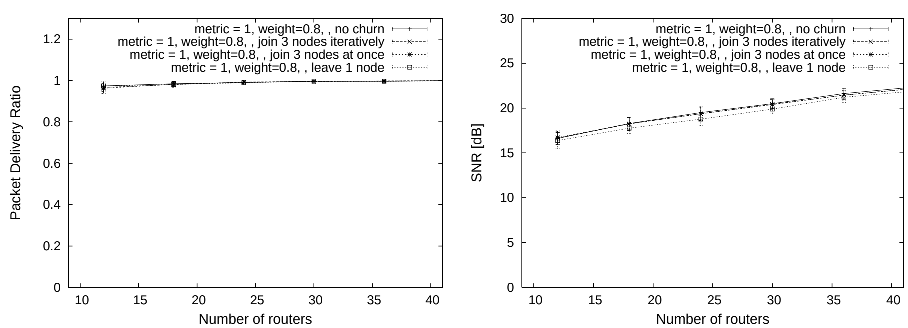


Fig. 12. Evaluation of performance when mesh routers join and leave. The results show that joins and leaves do not degrade performance in general.

without churn, we find that this amount of churn has no impact on the packet delivery ratio (see fig. 12). We explain this finding by the fact that the fraction of the routers that are backbone routers is rather small (around 12%) for the scenario size investigated and thus it is unlikely that a leaving router is part of the backbone.

For a more comprehensive review of evaluation results refer to [14].

6 Related Work

[5] proposes an algorithm for topology construction in IEEE 802.11 networks. However, due to high topology reconfiguration dynamics this algorithm is not suitable for our application scenario. A similar argument can be given for clustering based on idealized geographic assumptions [6] and topology construction on top of the Bluetooth technology [8].

Channel allocation for random medium access by heuristic algorithms is described in [9] and [10]. However, we cannot assume random medium access.

7 Discussion and Further Work

In this paper, we have proposed and evaluated a balanced greedy algorithm for a self-organizing topology construction and channel allocation in a network formed by routers that are equipped with multiple IEEE 802.16 interfaces. The routers are designed to connect portable UMTS/GSM base stations to enable voice communication for rescue forces in disaster recovery scenarios. To evaluate the proposed algorithm, we have conducted QualNet simulations for scenario sizes up to 40 routers among which 4-7 are gateways to the wired network. With the settings preferred by our industry partner (25 mW transmission power, 12 orthogonal channels of 10 MHz width in the 5.8 GHz band), we have found for random router placements that

- placing twelve routers per square kilometer is in most cases sufficient to connect UMTS/GSM base stations from routers to gateways.
- modifying the path metric to account for the traffic load on the gateways significantly improves the overall packet delivery ratio. The details in implementing this trade off between path quality and gateway load has negligible impact on the overall network performance in the investigated scenario sizes.
- introducing a limited amount of churn, once the network has been set up, e.g. such as adding three more routers to the network, or removing one router from the network, does not lead to significant overall performance degradation.

For a more comprehensive review of evaluation results refer to [14].

As a next step, we head towards implementing the algorithm in a distributed environment before porting it onto our industry partner's routers.

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