Impact of Gateways Placement on Clustering Algorithms in Wireless Mesh Networks

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Abstract—**In wireless mesh networks, designing algorithms that efficiently balance the traffic loads among a given set of network gateways is a challenging problem. Links interfere, transfer capacity is limited, and traffic demands vary overtime. The position of the gateways also affects the overall network performance as a result of its direct impact on the way routers are associated to gateways. In this paper, we investigate the performance of several routers-to-gateways association heuristics in relation with different gateway placement algorithms. We show that if bounds on the number of hops between routers and gateways exist, load-based heuristics perform the best. In general cases however, interference-based approaches provide better load balancing.**

I. Introduction

Interest in Wireless Mesh Networks (WMNs) has been growing over the past few years because of the wide range of applications they enable. The possibility of providing network connectivity practically everywhere with minimum deployment time and initial investment has attracted many community networks [8] and industrial groups [9]. However, the gain in deployment flexibility is counterbalanced by the necessity to deal with the unreliability inherent in wireless transmissions. This partly results from environmental interference and partly from the presence of multiple devices competing to simultaneously transmit on the same frequency band. In WMNs, users traffic is expected to be primarily outbound and therefore transiting through a network gateway. This unique property offers the incentive to study the deployment of multiple gateways to achieve better load distribution and hence improve the overall network utilization.

One challenging issue in traffic management is to minimize the network congestion level so as to accommodate future traffic growth. This relates in WMNs to the problem of associating routers to gateways such that the maximum link utilization is minimized (Fig. 1). We define link utilization as the amount of bandwidth used by all traffic demands routed through and interfering with a given link with respect to the total capacity of the link. In this context routers have the primary role of aggregating traffic from users directly associated with them and forwarding the aggregated traffic towards the destination. Gateways are routers that establish a bridge between different networks, typically between a wired network and the wireless mesh network. The association algorithm that determines to which gateway a router directs its traffic can, in certain cases, lead to a radically different network performance. For instance, many routers may be geographically close to one particular gateway. However, sending the traffic of some of them to a more distant, but lightly-loaded gateway, might lead to a better utilization of network resources.

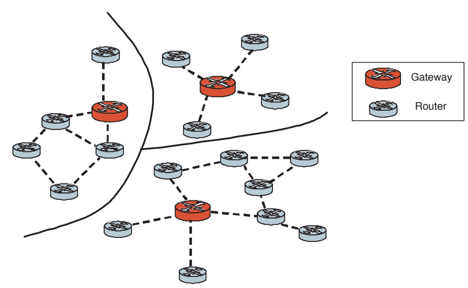

Fig. 1. Routers to gateways association

The performance of routers-to-gateways association algorithms is also impacted by the position and number of gateways. Two general approaches for the selection of gateways can be envisioned. The gateways can be optimally selected among a set of already deployed routers so as to minimize some predetermined metrics (e.g. number of hops). They can also be chosen in a more greedy way (in dense neighborhoord for instance) without fixed bounds on the distance between gateways and routers. In this paper, we are interested in investigating the weight of gateways placement algorithms on the performance of routers-to-gateways association heuristics from a traffic engineering viewpoint.

Our contribution is the following. We implemented several routers-to-gateways association heuristics and several gateways placement algorithms. Using the network topology of an already-deployed network (city of Chaska), we show that if the distance between the gateways and the routers can be bounded, load-based algorithms perform the best. However, in situations where the distance between the routers and the gateways is not constrained, interference-based approaches lead to better load distribution.

The remainder of the paper is organized as follows. In Section II, we present several routers-to-gateways heuristics. In Section III, we introduce the gateway placement algorithms and show the result of our simulations. Section IV concludes this paper.

II. Clustering Algorithms for Routers-to-Gateways Association

We designed several clustering heuristics that associate routers to gateways. We define a cluster as a network partition containing a set of connected routers and exactly one gateway. By construction, a router is member of only one network partition.

We focused on centralized approaches as they seem particularly appropriate in wireless mesh networks given the static nature of the backbone network and the specific traffic characteristics (the data traffic transiting mainly between the routers and the gateways). We consequently designed centralized routers-to-gateways association heuristics based on parameters such as Euclidean distance, number of hops, traffic load and interference level.

We categorize the algorithms as follows:

- Position-based approaches: routers are assigned to gateways based on their proximity either in terms of hops, or in terms of Euclidean distance.
- Load-balanced approaches: routers are assigned to gateways so that the traffic load directed to the gateways is distributed as uniformly as possible.
- Interference-based approaches: routers are assigned to gateways so that the inter-node interference is minimized.

A. Position-based Heuristics

Position-based heuristics differ according to the level of information they require to associate a router to a gateway. Two main options consist in using either the number of hops or the geographic distance (typically Euclidean distance) as decision factor. Each of these parameters has its pros and cons as we will further discuss, which, depending on the capabilities of the network devices (in particular the presence of positioning hardware), explains the preference of one approach over the other one.

1) Number of hops: Traditionally, the number of hops has been used as routing metric due to its easiness of computation. Many routing algorithms have been developed that compute efficiently the number of hops between any source and any destination. Its obliviousness to the network characteristics leads to the setup of stable routing paths whose reconfiguration is mainly triggered by hardware failures or the appearance of congestion points. However despite its simplicity and the low-overhead involved that represent undeniable advantages in wireless networks, failing to account for the network characteristics can result in congested paths responsible for network performance degradation.

The heuristic works as follows: A router is associated to the closest gateway in terms of hops (on a graph it corresponds to the number of edges of unit weight between two nodes). If several gateways are at the same distance from the router considered, one is selected at random.

2) Euclidean Voronoi Diagram: The decision to associate a router to a gateway can also be based on its localization. This implies that either the routers are equipped with localization devices such as GPS, or that there exist localization algorithms implemented that enable a router to determine its position. Although this approach comes at the cost of additional hardware or overhead, as the position of the routers is static in wireless mesh networks, the cost of getting localization information will be amortized over time as it needs to be obtained only at the deployment time (or in case of hardware failure). The drawback of this approach is that in the case where the routers are not uniformly distributed, choosing the closest gateway as destination may lead to longer paths than if a decision was made on the number of hops.

The heuristic works similarly as the Shortest-Path heuristic except that Euclidean distance is used to determine the gateway a router will be associated with. A post-processing step is implemented in order to guarantee that the resulting clusters are connected.

B. Load-balanced Heuristics

The load can be also used as parameter in the routing decision. The term “load” refers here to different parameters such as the number of routers supported by a gateway, or the amount of traffic sent by the routers to a particular gateway. We designed two heuristics based on these parameters: Load-adaptive Multiplicatively Weighted Voronoi clustering and Node-adaptive Multiplicatively Weighted Voronoi clustering.

1) Load-adaptive Multiplicatively Weighted Voronoi clustering: Assuming that the traffic load is mainly directed towards the gateways, load-balancing can be achieved at the gateways by associating routers to gateways based on their traffic demands. This approach presents the advantage of avoiding sending all the traffic towards a subset of gateways and therefore triggering packet losses due to network congestion.

The heuristic works as follows: For each gateway p and for each node X we compute the distance $d(p,X)w(p)$ where $d(p,X)$ is the Euclidean distance and $w(p)$ is a weight. $w(p)$ is computed as follows: $w(p) = (\sum \delta(i,p)L(i))/\sum L(i)$ with $L(i)$ the load at node i and $\delta(i,p) = 1$ if node i is associated with gateway p, 0 otherwise. A more heavily loaded gateway will consequently have a greater weight. At each iteration, a router (randomly chosen among the ones at shortest distance from a gateway) is associated to a gateway and the weight of the remaining routers (not already assigned) is recomputed.

2) Node-adaptive Multiplicatively Weighted Voronoi clustering: The router-to-gateway association decision can also be based on the number of routers already supported by a gateway. This approach presents the advantage of being simple, easily computable, and incurs a minimum overhead. Ignoring the traffic load at the routers provides a stable configuration as the routers have fixed positions, but this can lead to congestion situations and unbalanced traffic distribution.

The heuristic is similar as the previous one with the difference that we assume unit traffic loads, i.e. that $L(i) = 1$ for all i.

Algorithm 1 Voronoi Clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
for each node i in V do
    for each gateway do
        calculate distance to gateway
    end for
end for
associate node i with the gateway k with min distance
Calculate nb Nodes not connected
while Nb Nodes not connected > 0 do
    for each node not connected do
        nbNodesNotConnected –;
        check connectivity with other gateway and associate
        to the closest one if possible
        if not Connected then
            nbNodesNotConnected ++;
        end if
    end for
end while
```

C. Interference-based Heuristics

Associating a router to a gateway has an impact not only on the gateway, but also on all the routers along and at interference range of the path leading from the router to the gateway. We therefore designed two heuristics aiming at minimizing the interference by avoiding the zones where the traffic load is the heaviest.

1) Forces-based clustering: In this heuristic we modeled the impact of the concurrent traffic flows by a force defined as a function of the traffic load and of the distance between two routers. As a result, a router with heavy traffic load will push its neighbors to route their traffic towards less loaded areas. The heuristic works as follows. Each node has a charge $-f_i$, that corresponds to its traffic demand. The rationale behind this setting is that the greater the load at a node, the more resource it consumes. Therefore, other neighboring nodes would have to compete more to access the medium, which might impact their performance. A better load balancing avoiding the congested zones would consequently result in a better network performance. We model this competition for network resources by repulsive forces. An example is depicted in Fig. 2. Since traffic flows are directed towards gateways, the gateways exert an attractive force on the routers. Each gateway has a charge -$g_i \sum f_i / \sum_i g_i$, where g_i is the available bandwidth. The gateways with higher bandwidth consequently have a greater attraction force. For each router i, we calculate the force applied to it, which corresponds to the sum of all the repulsive forces exerted by the remaining routers ($\sum f_i f_j / d(i,j)^2 \vec{u_{ji}}$) plus the attractive forces from the gateways, with $d(i,j)$ the number of hops between router i and j. The sum of these forces results in a force that points towards a direction along which a router should direct its traffic. The gateway that is the closest to this direction is selected by the router as destination. However, we introduced some flexibility in the choice of the gateways in order to prevent choosing a far-away gateway closer to the targeted direction over a gateway at a closer proximity but slightly further off the targeted direction.

Algorithm 2 Force-based clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
for each node i in V do
    for each node j in V\{i} do
        calculate attraction force
        associate nodes to the gateway it is attracted the most
    end for
end for
Calculate nb Nodes not connected
while Nb Nodes not connected > 0 do
    for each node not connected do
        nbNodesNotConnected –;
        check connectivity with other gateway and associate
        to the one it is the most attracted to
        if not Connected then
            nbNodesNotConnected ++;
        end if
    end for
end while
```

2) Potential-based clustering: We use the same underlying idea to derive this algorithm as the one used for the Forces-based algorithm except that we assign to each edge (i, j) a weight called *potential(i,j)* which represents the difference of potentials between the two endpoints. For edge (i, j), $potential(i, j) = || - f_i - f_j|| / d(i, j)$, with $-f_i$ and $-f_j$ the traffic demands of node i and node j respectively. The potential on each edge therefore reflects the intensity of the traffic load it is susceptible to carry. Edges with high potential should therefore be avoided. The gateways are interconnected by wires of infinite capacity which can be represented on a graph by edges of weight 0. We then run Kruskal's algorithm to define the minimum spanning tree therefore removing the edges with high potential [5]. This determines the gateway a router should send its traffic to.

III. Evaluations

A. Gateways Placement Algorithms

We compared the performance of the heuristics for different gateways placement strategies.

1) **Recursive Dominating Set** [1]: At each iteration, the set of potential gateways is selected by computing the minimum dominating set of the graph resulting from the previous iteration. Since the minimum dominating set is a NP-Hard problem, a greedy approach similar to Chvatal's algorithm is implemented [3]. At each

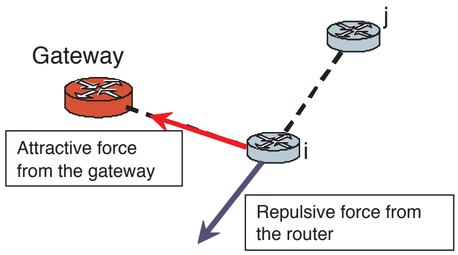

Fig. 2. Example of forces interaction: the gateway exerts an attractive force on Node i whereas Node k exerts a repulsive force

Algorithm 3 Potential-based clustering

INPUT: Graph (V,E)
OUTPUT: Clusters
for each node i in V **do**
  for each node j in $V \backslash \{i\}$ **do**
    calculate attraction force
  end for
end for
for each edge (i, j) in E **do**
  calculate potential
end for
run Kruskal's algorithm

iteration, the node that covers the greatest number of remaining uncovered nodes is selected to be part of the dominating set. A constraint is set on the maximum path length between a router and the gateway. The algorithm terminates when this constraint is violated.

2) **Iterative Greedy Dominating Set** [2]: Given a constraint R on the path length, the heuristic computes the minimum dominating set of the power graph $G^R(V^R, E^R)$. It selects iteratively the node that contains the greater number of uncovered remaining nodes in its R-neighborhood.
3) **Augmenting Placement** [4] [7]: This heuristic is similar to the iterative greedy dominating set heuristic, except that the augmenting algorithm does not make a greedy move in the next placement of additional gateways. Any node that reduces the number of uncovered nodes is considered.
4) **Greedy Placement**: A fixed number of gateways is chosen among the set of routers based on the number of neighbors they are connected to and based on their geographical locations. The routers with the highest number of neighbors are first chosen. All the routers located within a certain number of hops of the already chosen routers can not subsequently be elected as gateways.

B. Simulation Environment

To solve the linear programs, we used the default algorithm provided by Matlab based on the simplex method. The route computation is performed in a centralized manner. This allows to focus primarily on the performance of the algorithms. We also assume a 2-hop interference model, i.e. all the nodes at transmission range of the sender and receiver should remain silent for the data transmission to be successful.
We perform our simulations in a realistic environment using a network topology taken from an existing deployed network from the city of Chaska, Minnesota [6]. The network is composed of 195 routers.

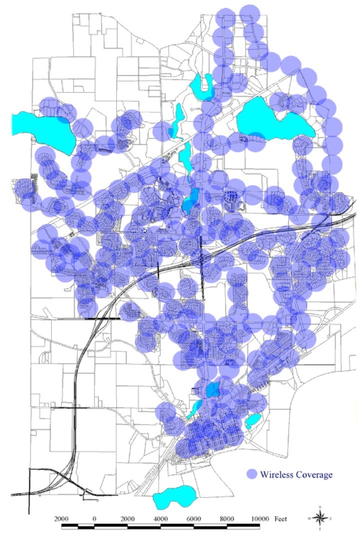

Fig. 3. Wireless coverage of Chaska and its neighboring communities

We set the maximum path length to 5 for the different gateways placement algorithm except for the greedy approach. Given the network topology considered in this paper, the recursive and iterative greedy dominating set approach resulted in the placement of 5 gateways whereas the augmenting placement algorithm resulted in the placement of 7 gateways. Maximum traffic loads were therefore adjusted in order to remain under or close to congestion level.

A closer look at the maximum link utilization (Fig. 4, Fig. 5, Fig. 6 and Fig. 7) shows that if the gateways placement is based on node proximity (i.e. the number of hops between gateways and routers is restricted), load-based approaches perform the best. However, if the placement of the gateways is greedy, the forces-based heuristic performs the best. This can be explained by the fact than when the gateways are more uniformly distributed and distance from routers to gateways is restricted, congestion is more likely to happen at the gateways. Consequently the simplest approaches perform the best. However, whenever the network extends and distances are not constrained, congestion-avoidance strategies perform the best. Moreover, we can observe that overall the forces-based heuristic results in a more uniform traffic distribution as reflected in the standard deviations in Fig. 8, Fig. 9, Fig. 10 and Fig. 11.

IV. CONCLUSIONS

Wireless mesh networks represent an attractive solution to address the last mile connectivity issue. However, limited link capacities still remain a concern as the number of end systems

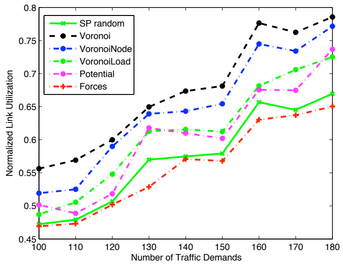

Fig. 4. Greedy gateway placement: max link utilization

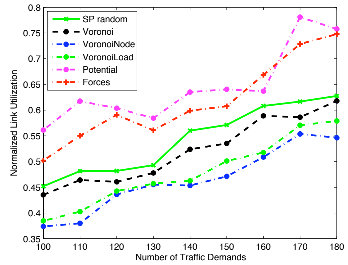

Fig. 5. Gateway placement based on recursive dominating set heuristic: max link utilization

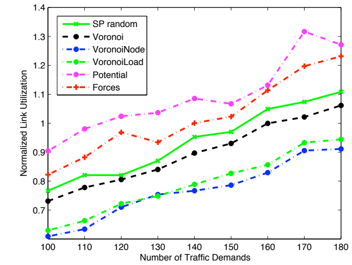

Fig. 6. Gateway placement based on iterative greedy dominating set: max link utilization

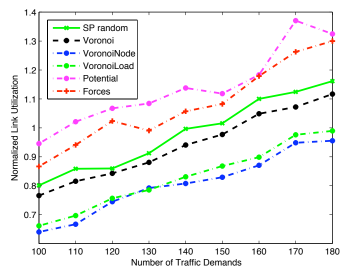

Fig. 7. Augmenting gateway placement: max link utilization

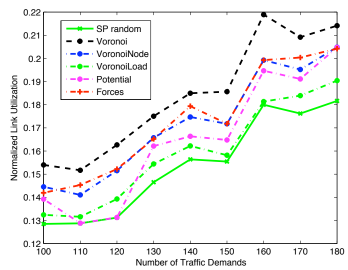

Fig. 8. Greedy gateway placement: standard deviation on the max link utilization

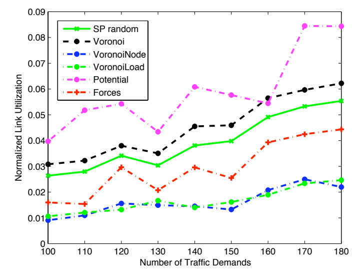

Fig. 9. Gateway placement based on recursive dominating set heuristic: standard deviation on the max link utilization

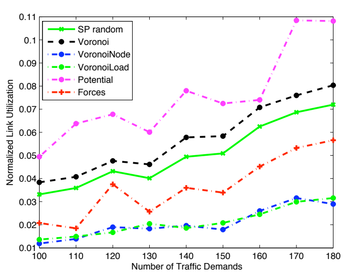

Fig. 10. Gateway placement based on iterative greedy dominating set: standard deviation on the max link utilization

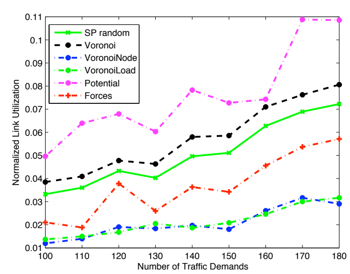

Fig. 11. Augmenting gateway placement: standard deviation on the max link utilization

increases and bandwidth requirements become more stringent. The presence of multiple gateways can be exploited to balance the traffic more evenly. Each gateway can be assigned a channel and routers can subsequently be assigned to a gateway depending on criteria such as Euclidean distance, number of hops or traffic load. One question that arises is the impact of the placement of gateways in the design of routers-to-gateways association algorithms. To address this question, we implemented four different gateways placement algorithms and evaluated a set of routers-to-gateways association heuristics. We showed that if the number of hops between the routers and the gateways is limited, then load-based approaches perform the best. However, in situations where the number of gateways is fixed and paths length increases, the network performance in terms of utilization can be improved by congestion-avoidance strategies.

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