Gateway Node Selection for Improving Traffic Delivery Ratio in Wireless Mesh Networks[*]

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Abstract - In this paper, we establish the gateway selection problem in the single radio single channel wireless mesh network: given a wireless mesh network and a desired delivery ratio, the goal is to select minimal number of non-gateway nodes and upgrade them to gateway nodes in order to improve the delivery ratio of the network to a given threshold. This problem is different with the previous gateway placement or deployment problem for we focus on the number of gateway nodes in an existing network. We formulate this problem as a mathematical programming and show that it's NP-hard. Then we propose three algorithms to solve this problem and give the simulation results to evaluate the performance of these three algorithms.

Index Terms - WMN, mathematical programming, greedy algorithm, k-median algorithm

1. Introduction

A WMN [1] consists of a set of mesh routers (called routers), which form a wireless backbone via wireless communication among them. Some of the routers (called gateways) have wired connections to the Internet. Clients can use the WMN to access the Internet by connecting to any of the routers and then all the traffics produced by the clients are aggregated and go through the gateways. Thus gateways have fixed bandwidths that have to be shared by all the clients via routers, a WMN may be unexpectedly congested at a certain gateway even if every mesh routers provide enough throughput capacity as the clients' usage grows. So the locations and quantity of gateways play crucial roles in WMN. On the other hand, it's more expensive to set up a gateway than a mesh router in the WMN for the gateway can connected Internet directly. Then it is necessary to minimize the number of gateways used in the WMN. All these facts above give us sufficient reason to focus on the gateway selection problem in an existing network.

In this paper, we study the gateway selection problem as follows. We give an existing wireless mesh network which includes a set of mesh routers and gateways that are already installed. Each router has equipped an additional interface for wired connection which means we could upgrade it to be a gateway if necessary. Suppose we know the clients traffic demand for each router. The problem is to select minimal routers and upgrade them to be gateways, such that the delivery ratio of each router reaches a desired level. This is a hard problem, because even the gateway deployment problem in an un-existing network is proved NP-hard and our problem

must to select and deploy the gateway in an existing network. We formulate our gateway selection problem as a mathematical programming and obtain an exact solution for this problem. Then, through the routing result when maximize the minimal delivery ratio of the network, we could find the most congested router in the existing network and upgrade it greedily. For there are many previous gateway deployment methods, we also could apply those algorithms into our problem.

The rest of the paper is organized as follows. The related work is reviewed in Section 2. We describe our system architecture in Section 3 and formulate our upgrade gateway problem as a mathematical programming in Section 4. An exact algorithm and two heuristic algorithms are proposed in Section 5. Simulation results are shown in Section 6 and we conclude the paper in Section 7.

2. Relate Work

In the literature, many works discussed how to deploy or place the gateways in a WMN that could optimize the throughput or satisfy throughput demand, such as [2], [7], [4], [5], [6], [8], [9], [10].

He et al. [4] studied the gateway deployment problem that how to minimize the number of gateways while satisfying the mesh router Internet throughput demand. They model the gateway placement problem as an integer linear program problem and develop two heuristic algorithms. A contribution should be mentioned in this paper is they have proved that the optimal gateway deployment problem in WMN is NP-hard by a reduction from the Capacitated Facility Location Problem (CFLP) [11].

Li et al. [5] addressed the problem of gateway placement for throughput optimization in multi-hop wireless mesh network. More specifically, given the mesh backbone and the number of gateways, they study how to place the gateways in order to achieve optimal throughput under interference in the network. Their goal is to make the total throughput is maximized while it also ensures a certain fairness among all mesh nodes. After formulating the problem as a LP, they give two greedy link schedules.

Other researchers also studied the problem of gateway placement while ensuring different requirements. [2], [9] preserve quality-of-service (QoS) requirements, [7] guarantees

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the access points' bandwidth requirements and [10] aims at gateway placement problem in two separate settings: either minimizing communication delay or minimizing communication cost.

All these previous works discuss the gateway placement problem before the backbone of the WMN is constructed and they use various criterions to place the gateways in order to obtain a WMN with good performance. Once the gateways are located, the throughput of network, i.e. the quality of service provides to the clients is fixed. As the network usage grows, the planned WMN may not still satisfies the new demand of clients. So the network designers need to improve an existing mesh network to provide additional capacity. Robinson et al.[8] studied the problem of adding new capacity points to an existing mesh network and present two online gateway placement algorithms that use local search operations to maximize the capacity gain on the network.

In this paper, we consider the gateway upgrade problem using delivery ratio to measure the network's quality of service. We study how to upgrade minimal number of mesh routers to gateways in order to improve the delivery ratio of the WMN to a desired level. This problem can be formulated as a 0-1 integer programming and obviously it's NP-hard from the result in [4].

3. System Architecture

A wireless mesh network typically consists of a number of static wireless mesh routers and end mobile clients. The static wireless routers are equipped with traffic aggregation capability to provide network connectivity to mobile clients within their coverage areas. The mesh routers form a multihop wireless backbone to route the traffic from clients to the Internet (upstream traffic), or from the Internet to clients (downstream traffic). Some of the routers called gateways are directly connected with the Internet. Therefore, in such networks, traffic is mainly routed by the wireless backbone between mobile clients and the Internet through gateways.

In this paper, we consider *single radio* and *single channel* wireless mesh network, that is, each mesh router is equipped with a single radio and all routers use the same channel. The backbone consists of N mesh routers (nodes), M of which are gateways, We denote the traffic demand of node u by λ_u and the transmission capacity of it by B_u. The traffic demand λ_u may be the sum of the upstream and downstream traffic loads. We define α_u as the delivery ratio of node u corresponding to traffic demand λ_u, thus $\alpha_u \lambda_u$ represents the actual traffic of node u that goes through gateways. We also denote the capacity of the communication link (u, v) as C_{uv}.

4. Problem Formulation

Our objective is to upgrade minimal number of mesh routers to gateways in order to improve the performance of the existing wireless mesh network, such that the minimum delivery ratio of the nodes in this network can reach a given threshold α. We model the backbone of the WMN as a undirected graph $G = (V, E)$, where V is the set of mesh routers, $S \subset V$ is the set of gateways. A link $(u, v) \in E$ from node u to node v in G indicates that node u, v is within the transmission range of each other. Let l_u be a 0-1 variable that indicates whether mesh node u is a gateway or not, $u \in V$, that is:

$$l_u = \begin{cases} 1, & \text{if node u is a non - gateway node;} \\ 0, & \text{if node u is a gateway node} \end{cases}$$

Obviously, $l_u = 0$ for $u \in S$ and we want to determine the value of l_u for $u \in V\text{-}S$.

The objective is to upgrade minimal number of non-gateway nodes to the gateway nodes such that the delivery ratio at all nodes can reach a given threshold. This objective is equivalent to maximizing the number of the non-gateway nodes in the network:

$$\max \sum_{u \in V} l_u \qquad (1)$$

We use f_{uv} to denote the amount of flow from node u to node v through the link $(u, v) \in E$. Since each non-gateway router is also responsible for routing for other routers, the total flow on its outgoing links must be equal to the total flow on its incoming links plus its own traffic demand:

$$l_u \cdot \left(\sum_{w \neq u} f_{uw} - \sum_{v \neq u} f_{vu} - \alpha_u \lambda_u \right) = 0 \quad \forall u \in V \qquad (2)$$

For any non-gateway node u, it is equipped with only one interface with transmission capacity of B_u. This fact will impose the following capacity constraint:

$$\alpha_u \lambda_u + \sum_{w \neq u} f_{uw} + \sum_{v \neq u} f_{vu} \leq B_u \quad \forall u \in V / S \qquad (3)$$

With respect to gateway nodes, they are the destination of any traffic and thus have no outgoing links, this constraint can be simplified as the following:

$$\alpha_u \lambda_u + \sum_{v \neq u} f_{vu} \leq B_u \quad \forall u \in S \qquad (4)$$

Using variable l_u, we can combine (3) and (4) as follwing:

$$\sum_{w \neq u} f_{uw} \cdot l_u + \sum_{v \neq u} f_{vu} + \alpha_u \lambda_u \leq B_u \quad \forall u \in V \qquad (5)$$

Interference is another factor restricting the delivery ratio of the mesh network. For link $(u, v) \in E$, let I_{uv} denote the set of links interfered by link $(u, v) \in$. Since links in I_{uv} can not transmit simultaneously, therefore, we have the following interference constraint:

$$f_{uv} + \sum_{(x,y) \in I_{uv}} f_{xy} \leq C_{uv} \quad \forall (u, v) \in E \qquad (6)$$

Finally, we give the constraints of variables f_{uv}, α_u and l_u:

$$0 \leq f_{uv} \leq C_{uv} \quad \forall u, v \in V \qquad (7)$$

$$\alpha \leq \alpha_u \leq 1 \quad \forall u \in V \tag{8}$$

$$l_u \in \{0,1\} \quad \forall u \in V \tag{9}$$

Theorem 1. *The Gateway Selection Problem (GSP) in the wireless mesh network is NP-hard.*

He et al.[4] have proved the Internet gateway deployment problem is NP-hard. And our GSP is a variety of the gateway deployment problem for we also should choose the suitable location (mesh router) to deploy (upgrade) the gateway, so it obvious that our GSP is also an NP-hard problem.

5. Our Proposed Algorithm

In this section, we first give an exact algorithm based on our mathematical programming (MP). Then we design two heuristic algorithms, one is a greedy algorithm which upgrades the traffic congested nodes step by step, and another is a k-median based algorithm.

A. Algorithm based on MP model

For we have formulated the problem as a mathematical programming, we can obtain the exact solution by solving the mathematical programming. We first give an algorithm based on optimal toolbox in MATLAB as follows.

We first need to compute the max-min delivery ratio α for the existing network. Denote the threshold of delivery ratio as α_0. If $\alpha \geq \alpha_0$, the existing network satisfies the demand; otherwise, we use mathematical programming (MP) (1), (2), (5)-(9) to compute the optimal solution.

The mathematical programming for solving the max-min delivery ratio of nodes in the network is formulated as following:

$$\max \min \sum_{u \in V} \alpha_u \tag{10}$$

$$\sum_{w \neq u} f_{uw} - \sum_{v \neq u} f_{vu} - \alpha_u \lambda_u = 0 \quad \forall u \in V \tag{11}$$

$$\sum_{w \neq u} f_{uw} \cdot l_u + \sum_{v \neq u} f_{vu} + \alpha_u \lambda_u \leq B_u \quad \forall u \in V \tag{12}$$

$$f_{uv} + \sum_{(x,y) \in I_{uv}} f_{xy} \leq C_{uv} \quad \forall (u,v) \in E \tag{13}$$

$$0 \leq f_{uv} \leq C_{uv} \quad \forall u, v \in V \tag{14}$$

$$0 \leq \alpha_u \leq 1 \quad \forall u \in V \tag{15}$$

Algorithm 1: Algorithm based on MP model

Step 1: Maximize the minimum delivery ratio of nodes in *G* by MP (10)-(15) and obtain the max-min delivery ratio α. If $\alpha \geq \alpha_0$, go to step 3; otherwise go to step 2;

Step 2: Compute the minimal number of gateways by MP (1), (2), (5)-(9) in *G* and obtain the new gateway set *S**.

Step 3: Output the optimal solution *S**.

B. Greedy algorithm

Computational complexity of MP based algorithm is very high, so we design an efficient greedy algorithm to get an approximation solution. The basic idea of the greedy algorithm is to upgrade "congested" non-gateway nodes that the total flows on their up-links and down-links are close to the capacity when we maximize the minimum delivery ratio. In other words, we want to find the non-gateway node whose flow of its links is the most congest in the network. When there exists more than one non-gateway nodes that the total flow on their links is the same, tie-break is based on the following rules: 1)the node whose interference links is fewer than the others has higher priority; 2)the node who interferes with the fewest exist gateway nodes is upgraded first.

We use p_u to represent the priority of node *u*.

Algorithm 2: Greedy algorithm

Step 1: Maximize the minimum delivery ratio of nodes in *G* by MP (10)-(15) and obtain the max-min delivery ratio α. If $\alpha \geq \alpha_0$, go to step 3; otherwise go to step 2;

Step 2: Upgrade non-gateway nodes to gateway nodes:

　Step 2.1: For every non-gateway node $u \in V / S$, compute $p_u = \sum_{w \neq u} f_{wu} + \sum_{v \neq u} f_{uv}$.

　Step 2.2: Sort p_u for all non-gateway nodes *u*, that is $p_{u_1} \geq p_{u_2} \geq \cdots \geq p_{u_{|V/S|}}$.

　Step 2.3: Upgrade node u_1 to be a gateway node according to the rules.

　Step 2.4: $S \leftarrow S \cup \{u_1\}$, go to Step 1.

Step 3: Output the gateway set *S*.

We can see the main computation step is solving the maxmin ratio of network which is a linear programming, so the time complexity of Greedy algorithm is $O(|V|^3)$.

C. Algorithm based on k-median

If the number of gateways is given, gateway deployment problem can be reduced to the *k*-median problem and previous works have designed some approximation algorithms for this problem. We consider the *k*-median problem with a locality gap of 3+2/*p* [3]. This local search algorithm is based on repeatedly swapping *p* existing gateways for *p* spare gateways until no swaps can improve the solution. In our algorithm, because we should select the minimal number of gateways in an existing network, |*S*| of *p* should be fixed and we increase the value of *p* gradually until the delivery ratio of the network reaches the threshold. In each step, the main idea is to select |*S*| + *p* gateways to maximize the minimum delivery ratio on each node.

Algorithm 3: Algorithm based on *k*-median

Step 1: Maximize the minimum delivery ratio of nodes in G by
   MP (10)-(15) and obtain the max-min delivery ratio α.
   If $\alpha \geq \alpha_0$, go to step 3; otherwise go to step 2;

Step 2: Upgrade non-gateway nodes to gateway nodes:
   Step 2.1: Set $p = 1$.
   Step 2.2: Find $k = |S| + p$ gateways by applying local
      search *k*-median algorithm.
      Denote the local optimal value as α' and
      update gateway set as *S'*.
   Step 2.3: If $\alpha' \geq \alpha_0$, go to Step 3;

      otherwise $p = p + 1$, go to Step 2.2.
Step 3: Output the gateway set *S'*.

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6. Simulation Results

In this section, we evaluate the performance of our algorithms and the simulation is separated into two parts.

A. 10 (20) nodes graph

We consider static wireless mesh network with 10 nodes and 20 nodes randomly located in a $50 \times 50 m^2$ region, resulted a 10-node graph and 20-node graph, and a certain number of these nodes are selected randomly as gateways. The transmission range is set to be $25m$ and the interference range is assumed to be 2 times of the transmission range. According to this assumption, we can get the adjacent matrix and interference matrix of all the nodes in the network. In addition, the transmission capacity of each node is fixed to be 30 *Mbps* ($B = 30$ *Mbps*) and the traffic demand to be 10 *Mbps* ($\lambda = 10$ *Mbps*). We assume a simple wireless channel model in which link rates depend only on the distance between two nodes. Finally, we assume the gateway nodes have sufficient *wired* capacity.

Under these parameters, when there is only one gateway in both 10-node and 20-node graph, the max-min delivery ratio is 30% and 15% respectively. In order to make the upgrade process more clear, we assume there is only one gateway in the original graph. Then we increase the threshold of delivery ratio step by step, i.e. 10% a step. The result of three algorithms proposed in Table 1.

TABLE I: The Result Number of Gateways in Three Algorithms

α	10-node graph			20-node graph		
	MP	Greedy	*k*-median	MP	Greedy	*k*-median
10%	×	×	×	1	1	1
20%	×	×	×	2	2	2
30%	1	1	1	2	3	3
40%	2	2	2	3	3	3
50%	2	2	2	4	4	4
60%	2	2	2	4	4	5
70%	3	3	3	5	5	5
80%	3	3	3	6	6	6
90%	3	3	3	6	7	7

From the above table, we can see when size of graph is small, our Greedy algorithm and k-median based algorithm

work out the close results compared to exact optimal solution by MP based algorithm. Furthermore, we use two examples to describe the new upgrade gateways in the following Fig. 1 and Fig. 2. Red node in the graph is original gateway and blue nodes are the new gateways which are upgraded step by step to reach the threshold. Specially, we indicate the path of upgrade process in Fig. 1. The location of gateways and the path of upgrade show that the gateways trend towards an even distribution in the region and this observation matches the gateway placement strategies discussed in the previous works.
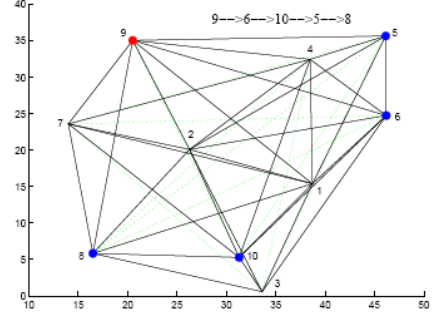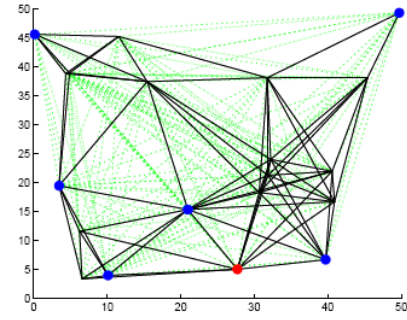

Fig. 1 10 nodes graph.

Fig. 2 20 nodes graph.

Finally, in Fig. 3 and Fig. 4, we give two trend lines with the parameters delivery ratio and gateway number. In Fig. 3, we can see upgrading one non-gateway node to gateway node could increase delivery ratio of the network at least 10%. This also emerges in Fig. 4 that the line in this figure is nearly linear which shows adding more gateways will evidently improve the performance of the network when the size of network is small.
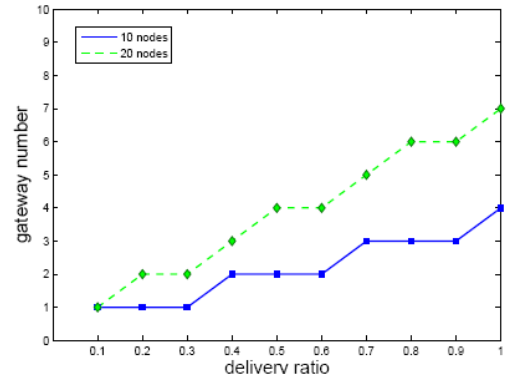

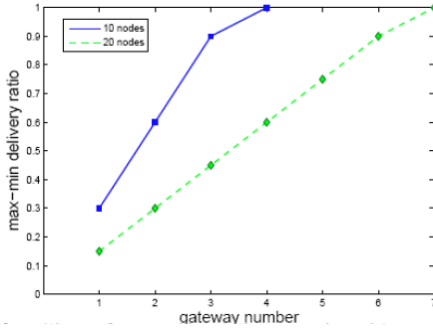Fig. 3 Trend line of gateway number with delivery ratio increasing.

Fig. 4 Trend line of max-min delivery ratio with gateway number Increasing

B. 50 (80) nodes graph

We locate 50 nodes and 80 nodes randomly in a $100 \times 100 m^2$ region, and 2 and 4 nodes are selected randomly as gateways to guarantee 10% original delivery ration of the network. The transmission range is still set to be $25m$ and the interference range is assumed to be 2 times of the transmission range.

Below we use curves to show the results of three algorithms in both these two graphs. We can see that the Greedy algorithm is better than k-median based algorithm. Because in Greedy algorithm, after each step of upgrading, we solve the maxmin delivery ratio problem in the network using the optimal tool-box which could work out an exact solution and it may counteract the error causes in the step which choose a congested node to upgrade according to its total traffic. Another the reason why *k*-median based algorithm is not so good is *k*-median algorithm is an approximation algorithm and the error caused by the approximation algorithm itself always exists in the iteration of *k*-median based algorithm.
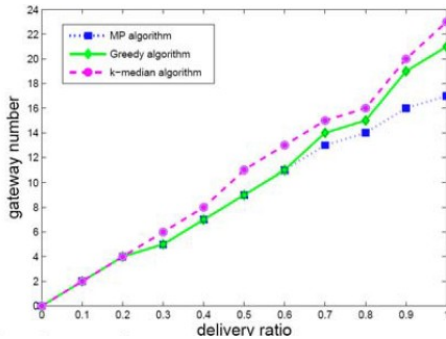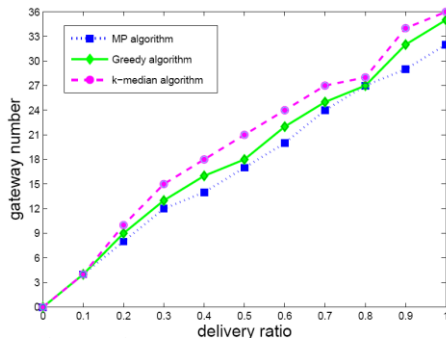

Fig. 5 50 nodes graph.

Fig. 6 80 nodes graph.

In real engineering application, it needs not to improve the delivery ratio much higher than the original level. Thus Greedy algorithm could be applied in this situation. Even if the size of the network is very large, we also prefer to Greedy algorithm for it runs in $O(|V|^3)$ time while *k*-median based algorithm should solve an NP-hard problem.

7. Conclusion

In this paper, we focus on gateway selection problem in the wireless mesh network that upgrade some existing non-gateway nodes to gateway nodes in order to improve the delivery ratio of network to a given threshold. We formulate the problem as a mathematical programming and prove that it's NP-hard. Then we propose an exact algorithm based on solving the problem by optimal tool box, and two heuristic algorithms–Greedy algorithm and k-median based algorithm. Comparing to the optimal solution worked out by the exact algorithm, the performance of Greedy algorithm is better than *k*-median based algorithm and Greedy algorithm is also superior to *k*-median algorithm in computational complexity.

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