A Gateway Placement Algorithm in Wireless Mesh Networks

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ABSTRACT

An innovative gateway placement scheme is proposed for wireless mesh networks (WMNs) in this paper. In the WMN model, a regular grid backbone network comprising of mesh routers overlays on an ad hoc network comprising of mesh clients; a certain amount of gateways is chosen among mesh routers to provide Internet access. Thus, given the number of gateways, the proposed gateway placement scheme provides a framework of maximizing the throughput of WMNs through proper placement of these gateways. The location of a gateway is determined based on a new performance metric called multi-hop traffic-flow weight (MTW). The MTW computation takes into account many factors that impact the throughput of WMNs, i.e., the number of mesh routers, the number of mesh clients, the number of gateways, traffic demand from mesh clients, locations of gateways, and possible interference among gateways. The performance of the proposed gateway placement scheme is evaluated through simulations. Experimental results show that it constantly outperforms other schemes with a large margin.

Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Network Architecture and Design – *Network communications, Network topology, Wireless communications, Wireless networks, Wireless mesh network.*

General Terms

Algorithms; Performance; Design; Theory

Keywords

Wireless mesh networks; Throughput; Gateway placement; Traffic scheduling

1. INTRODUCTION

In a wireless mesh network (WMN), a traditional ad hoc network is overlaid with an infrastructure network called mesh backbone. Mesh backbone comprises wireless mesh routers, which are powerful devices without constraints of energy, computing power, and memory. Usually they are distributed in a static and deterministic manner. WMNs offer all the advantages of ad hoc wireless networks plus many extra benefits from the infrastructure architecture. Wireless mesh backbone can be rapidly deployed with minimal cost and provides a robust, efficient, reliable, and flexible system that supports the network access for mesh clients. Mesh backbone can also provide mesh clients with various services and resources through their gateway and bridging functions. With infrastructure support, the complexity of communication protocols in mesh clients can be reduced significantly. All these advantages reinforce WMNs as a promising wireless technology for numerous applications, e.g. broadband home networking, community and enterprise networking, public Internet access, and so on. Figure 1 presents an example of a WMN in today's digital world.

Many research problems still remain open in WMNs [1]. Among them, one of the challenging research topics is to study the throughput of WMNs. Throughput capacity of multi-hop wireless networks has been studied by many recent works. Gupta and Kumar [2, 3] derived the per-node throughput capacity for static ad hoc networks. The throughput capacity of mobile ad hoc networks was analyzed by Grossglauser and Tse [4]. The capacity of hybrid ad hoc networks was investigated in [5, 6, 7]. All the above throughput results have been obtained as asymptotic value by assuming that the size of the network goes to infinity. Since real networks always have limited size, these asymptotic results provide very few information for practical network design. Further more, the above-mentioned throughput results cannot be applied to WMNs, because the network architecture of WMNs is much different from either conventional ad hoc networks or hybrid ad hoc networks. Compared with conventional ad hoc networks, WMNs are hierarchical networks in which there exist different types of communications among various nodes. In comparison with hybrid ad hoc networks, WMNs use wireless links instead of wired lines to connect backbone networks. In the throughput analysis of hybrid ad hoc networks, communication links among backbone nodes are assumed to have unlimited capacity, and such communications do not cause interference on other communications. However, these assumptions are no longer valid in WMNs.

The hierarchical architecture of WMNs also makes the placement of mesh backbone nodes a very interesting topic. Previously

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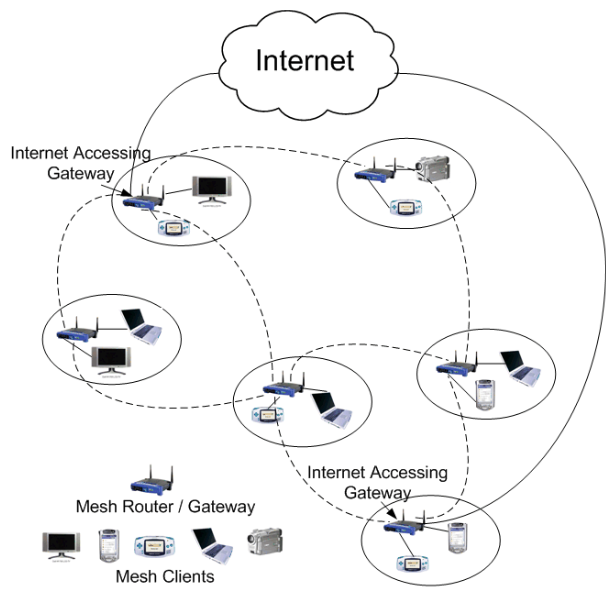

Figure1. A typical WMN

there were a number of similar studies, for example, placing Web proxies or server replicas to optimize clients' performance [8, 9, 10]. Another example is in regards to base station placement in cellular networks [11, 12, 13]. However, when wireless links replace wired links and multi-hop communications replace single-hop communications, more comprehensive traffic modeling schemes are required to solve the backbone nodes placement problem in multi-hop wireless networks. More recently the *Connected Disk Cover* (CDC) problem was investigated by Srinivas and Modiano [14]. CDC problem focused on network connectivity of WMNs by deploying the minimum number of backbone nodes. Bejerano studied gateway placement in multi-hop wireless networks [15]. In his work, network nodes were partitioned into minimal number of disjoint clusters that satisfied throughput and delay constraints.

Unlike all the above research work, in this paper we aim to develop a gateway placement algorithm for maximizing throughput of WMNs. To the best of our knowledge, little research work has been carried out along this direction. However, throughput is one of the most critical parameters that ensure the services of WMNs to meet the requirements of customers.

In this paper a non-asymptotic analytical model is first derived to calculate the throughput of WMNs. TDMA is assumed to schedule packet transmissions in mesh clients, mesh routers, and gateways. Two radio interfaces are assumed to be equipped on a mesh router so that it can communicate with a mesh client and a mesh router at the same time. Since gateways are the busiest routers in the network, an optimal TDMA scheme is first applied to all the gateways so that in each time slot simultaneous transmissions on gateways do not interfere with each other. In addition, the scheduling scheme guarantees that each gateway can be assigned a maximum number of time slots. Time slots assigned to a gateway are then split into separate small slots that are further assigned to all the associated mesh clients with this gateway. In this way, a certain amount of throughput is virtually guaranteed in the backbone for each mesh client. Similarly, a virtual throughput can also be reserved in communications between a mesh router and a mesh client. Finally, a feasible throughput of the WMN is obtained by choosing the smaller one of the above two throughputs.

With the throughput computation model, we derive a new performance metric called multi-hop traffic-flow weight (MTW) to take into account major factors that impact throughput of WMNs. Such factors include the number of mesh routers, mesh clients, and gateways as well as traffic demands from mesh clients, locations of gateways, and interference among gateways. Based on MTW, an iterative algorithm is proposed to determine the best location of a gateway. Each time a gateway is chosen to co-locate with the mesh router that has the highest MTW. Simulations are carried out in this paper to compare the proposed scheme with other schemes such as random placement, regular placement, and busiest router placement. Experimental results show that our gateway placement algorithm outperforms all these schemes with a large margin.

The rest of this paper is organized as follows. In Section 2, a typical WMN model is described and two problems for optimal gateway placement are formulized. A throughput computation model in WMNs is proposed in Section 3. The proposed gateway placement algorithm is described in Section 4. Numeric results are obtained and discussed in Section 5. This paper is concluded in Section 6.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1 Network Topology

A typical WMN model for Internet accessing is proposed as follows and is illustrated in Figure 2. N_c mesh clients are assumed to be distributed on a square $R=[0,l]^2$. R is partitioned evenly into $(l/l_s)^2$ small cells $R_s^j=[0,l_s]^2 \quad (j=1...(l/l_s)^2)$, and a mesh router is placed in the center of each cell. Let N_r denote the number of mesh routers, then $N_r=(l/l_s)^2$. In what as follows, we will limit the case of interests to that where $N_r \le N_c$, i.e., the number of mesh routers is smaller than that of mesh clients. Mesh routers constitute a wireless mesh backbone providing a wireless infrastructure for mesh clients. In each cell, mesh clients are connected to the mesh router like a star topology, i.e., no direct communication is available among mesh clients, and the mesh router works as a hub for mesh clients. Such a WMN is referred as an infrastructure WMN in [1], which will be very popular in future WMN applications. Among all the mesh routers, there are N_g routers wired to Internet, working as gateways. It is obvious that $N_g \le N_r$, i.e., the number of gateways cannot exceed the number of mesh routers.

Each mesh client is a data source and a data destination. All mesh clients are equivalent such that they always have the same amount of packets to send or receive during a certain time. Unlike mesh clients, mesh routers are neither data source nor data destination; they only route and forward data for mesh clients. All traffic is assumed to go through gateways. Each mesh router is associated with its nearest gateway such that it relays packets to or from it.

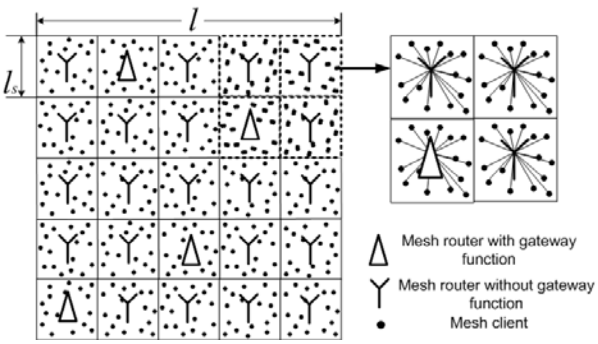

Figure 2. Network topology of an infrastructure WMN

Assuming that the shortest path routing is applied, the nearest gateway of a mesh router is defined as the gateway that the mesh router can access to by the minimal number of hops. In the situation that a mesh router has more than one nearest gateways, the traffic load of the router will be equally shared by all its nearest gateways. A mesh client is said to be associated with a gateway if its connected router is associated with the gateway. Hence, all traffic load of a mesh client will also be equally shared by all its potentially associated gateways.

In this paper the following definitions of communications will be frequently used:

- *Local communications*: it is referred as the communications between a mesh router and a mesh client;
- *Backbone communications*: it is referred as the communications between two mesh routers, which includes the communications between a gateway and a mesh router;
- *Downlink communications*: it is referred as the communications from a gateway to a mesh client, in which a data packet is first relayed among mesh routers in backbone communications and is then sent by a mesh router to one of its connected mesh clients;
- *Uplink communications*: it is referred as the communications from a mesh client to a gateway, in which a data packet is sent in the exact reverse direction as described in downlink communications.

2.2 Transmission Model

Each mesh router is equipped with two radio interfaces such that it transmits at W_1 bits/s in backbone communications and it transmits at W_2 bits/s in local communications. Each mesh client transmits at W_2 bits/s in local communications. We assume that W_1 and W_2 are orthogonal so that local communications do not interfere with backbone communications. Note that mesh routers and mesh clients use the same radio interface in local communications. In addition, mesh routers can receive packets from only one sender at a time and cannot transmit and receive packets simultaneously. The same constraint is imposed on mesh clients.

In either local communications or backbone communications, simultaneous transmissions are coordinated by the Protocol Model as defined in [3], i.e, if a transmission from node S_i to S_j is successful, then the following conditions must be satisfied: 1) $|S_i - S_j| \le r_i$; 2) for every other transmitting node S_k, $|S_k - S_j| \ge (1+\Delta)r_k$, where r_i and r_k correspond respectively to the transmission range of node S_i and S_k and Δ is a fixed positive constant that represents a guard zone in the Protocol Model.

2.3 Problem Formulation

Problem 1: Optimal gateway placement for maximizing aggregate throughput of WMNs, i.e. in the above WMN model, given N_c, N_r, N_g, W_1, W_2 and specific clients' distribution, routers' distribution, transmission, scheduling and routing protocols, N_g gateways are chosen among N_r mesh routers such that,

$$\sum_{i=1}^{N_c} TH(i, N_g)$$

is maximized, where $TH(i, N_g)$ denotes the per client throughput of the *i*th mesh client when N_g gateways are deployed.

Problem 2: Optimal gateway placement for maximizing the worst case of per client throughput of WMNs, i.e. in the above WMN model, given N_c, N_r, N_g, W_1, W_2 and specific clients' distribution, routers' distribution, transmission, scheduling and routing protocols, N_g gateways are chosen among N_r mesh routers such that,

$$\min_i TH(i, N_g)$$

is maximized.

3. TRAFFIC SCHEDULING FOR THROUGHPUT COMPUTATION

In this section, TDMA schemes are applied for traffic scheduling. Based on these schemes, we provide a framework for throughput computation in WMNs.

The WMN model indicates that all wireless mesh routers contend for the same wireless channel of capacity W_1 in backbone communications and all mesh routers and mesh clients contend for the same wireless channel of capacity W_2 in local communications. Therefore, the throughput of the *i*th mesh client when N_g gateways are deployed, denoted as $TH(i, N_g)$, is generally constrained by both W_1 and W_2. Since W_1 and W_2 are orthogonal, $TH(i, N_g)$ can be obtained by computing the throughput constrained by W_1 and the throughput constrained by W_2 separately, i.e.,

$$TH(i, N_g) = \min\{TH_{W_1}(i, N_g), TH_{W_2}(i)\},\ i = 1 \ldots N_c. \quad (1)$$

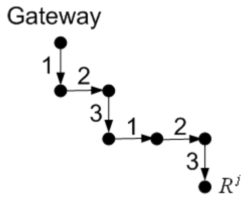

Figure 3. A TDMA scheduling scheme in backbone communications with $SRD = 3$

Here $TH_{W_1}(i, N_g)$ is defined as the throughput of the ith mesh client in backbone communications when there are N_g gateways in the WMN and $TH_{W_2}(i)$ is defined as the throughput of the ith mesh client in local communications. Note that $TH_{W_2}(i)$ is independent of N_g in the WMN model. (1) indicates that a feasible per client throughput can be achieved by taking the smaller one of $TH_{W_1}(i, N_g)$ and $TH_{W_2}(i)$.

Since both clients and routers cannot send and receive at the same time, W_1 and W_2 should be split for uplink and downlink communications respectively, i.e., c_1W_1 and c_2W_2 are assigned to downlink communications, and $(1-c_1)W_1$ and $(1-c_2)W_2$ are assigned to uplink communications, where c_1 and c_2 are some constants between 0 and 1. Generally, throughput of a mesh client should be obtained as the sum of uplink throughput and downlink throughput. Choosing the value of c_1 and c_2 requires knowledge on actual applications running on clients, which is beyond the objectives of this paper. It is assumed in the following of this paper that downlink traffic is dominant in the WMN. Therefore, most of W_1 and W_2 will be assigned to downlink communications and throughput is decided by downlink throughput, which is constrained by c_1W_1 and c_2W_2. This is not an uncommon case in today's applications of WMNs, for instance, in the application of Internet accessing. Please note that the methodology proposed in this section can actually be used to obtain throughput of WMNs when uplink and downlink traffic both present, however, with the above simplified model, we can focus on the illustration of our main ideas without distraction from trivial discussions.

3.1 Throughput in backbone communications

Time slots in backbone communications are first assigned to gateways so that no gateways interfere with each other. The TDMA scheduling scheme on gateways is assumed to satisfy the following two conditions: 1) Time slots are assigned to each gateway as equally as possible; 2) Under the condition of 1), each gateway should have as much as possible time slots for successful transmissions. In Section 4.2, an algorithm to obtain the sharing efficiency on all the gateways, denoted as $G_{eff}(k),\ k = 1...N_g$, is provided and is illustrated by an example, as depicted in Figure 6. In this algorithm, a traffic scheduling scheme satisfying the above two conditions is also constructed. In the scheme, the kth gateway can be guaranteed to have a number of time slots, which is equal to the total number of all time slots times $G_{eff}(k)$. Hence, the kth gateway is guaranteed to have an aggregate throughput of $G_{eff}(k) \times c_1W_1$ in backbone communications. By the TDMA scheme, interfering gateways share the same wireless channel while non-interfering gateways can transmit simultaneously.

In the next step, time slots of a gateway will be further split into small time slots to have the following two properties: 1) Each mesh client associated with the specific gateway should have separate small time slots for "interference free" transmissions; 2) Each of such mesh clients should achieve a common throughput in backbone communications, i.e., $TH_{W_1}(i_1, N_g) = TH_{W_1}(i_2, N_g)$, if mesh clients i_1 and i_2 are associated with the same gateway. It is assumed that a mesh router R^j has $N_C(j)$ connected mesh clients and it is located $N_{hop}(j)$ hops from its associated gateway. The second property requires that R^j be assigned $N_C(j) \times N_{hop}(j)$ small time slots if there are no simultaneous transmissions along the way from the gateway to R^j. Figure 3 shows that simultaneous transmissions can be scheduled, if R^j is more than SRD-hops away from its gateway. SRD is defined as *Slot Reuse Distance*, for instance, $SRD = 3$ in Figure 3. Therefore, the actual time slot that a R^j-connected mesh client need to meet the second property, denoted as $N_{hop}'(j)$, has the following relationship with $N_{hop}(j)$:

$$N_{hop}'(j) = N_{hop}(j), \ \text{if } N_{hop}(j) < SRD;$$
$$N_{hop}'(j) = SRD, \quad \text{if } N_{hop}(j) \geq SRD.$$

Hence, with the first property all mesh clients associated with a specific gateway require total $\sum_j N_C(j) \times N_{hop}'(j)$ small time slots for "interference free" transmissions in backbone communications. With the consideration that a mesh router may have more than one potentially associated gateways, the kth gateway can guarantee the following per client throughput for all its associated mesh clients in backbone communications:

$$TH_g(k) = \frac{G_{eff}(k) \times c_1 W_1}{\sum\limits_{\substack{j=\text{all associated routers}\\ \text{with the } k\text{th gateway}}} (N_C(j) \times N_{hop}'(j) \div N_g(j))} , \qquad (2)$$

Where $N_g(j)$ denotes the number of potentially associated gateways with the mesh router R^j.

Assuming the ith mesh client is connected with the mesh router R^j, then the throughput of the ith mesh client in backbone communications is given as follows:

$$TH_{W_1}(i, N_g) = \frac{\sum_{k=1}^{N_g(j)} TH_g(k)}{N_g(j)}. \qquad (3)$$

3.2 Throughput in local communications

A TDMA scheduling scheme is applied and guarantees successful transmissions in local communications.

Separate time slots are first assigned to different mesh routers so that simultaneous transmissions can only be carried out in cells

1	2	1	2	1	2
3	4	3	4	3	4
1	2	1	2	1	2
3	4	3	4	3	4
1	2	1	2	1	2
3	4	3	4	3	4

Figure 4. A TDMA scheduling scheme in local communications with $CRF = 4$

that have enough distance in between, i.e., simultaneous transmissions can only exist in cells that are $(\sqrt{CRF} - 1)$ cells apart, where CRF is defined as *Cell Reuse Factor*. Hence, in downlink communications, each mesh router can only have one slot every CRF time-slots, as depicted in Figure 4, here $CRF = 4$.

The above slot is further split into separate small-slots. Assigned a different small-slot, each mesh client is guaranteed to obtain successful reception from its associated mesh router. Therefore,

$$TH_{W_2}(i) = \frac{c_2 W_2}{CRF \times N_c(j)}, \; i = 1 \ldots N_{c,} \qquad (4)$$

Note that with the above TDMA scheme, all the mesh clients associated with the same mesh router will have the same throughput in local communications, i.e., $TH_{W_2}(i_1) = TH_{W_2}(i_2)$, if clients i_1 and i_2 are associated with the same mesh router.

3.3 Throughput in WMN

Combining equations (1) ~ (4), a feasible throughput of the *i*th mesh client in the WMN can be obtained as follows:

$$TH(i, N_g) = \min\{ \sum_{k=1}^{N_g(j)} \frac{G_{eff}(k) * c_1 W_1}{\sum_{\substack{j = \text{all associated routers} \\ \text{with the } k\text{th gateway}}} (N_C(j) \times N_{hop}{}'(j) \div N_g(j))} / N_g(j), \frac{c_2 W_2}{CRF \times N_c(j)} \},$$

here *i*th mesh client is assumed to be connect with the mesh router R^j.

When all mesh routers are chosen as gateways, i.e., $N_g = N_r$, throughput of the *i*th mesh client is only constrained by local communications, i.e., $TH(i, N_r) = TH_{W_2}(i)$. Therefore, an upper bound is obtained for the aggregate throughput:

$$\begin{aligned} \sum_{i=1}^{N_c} TH(i, N_g) &\le \sum_{i=1}^{N_c} TH_{W_2}(i) \\ &= \frac{c_2 W_2}{CRF} \times \sum_{j=1}^{N_r} u(j), \end{aligned}$$

Where $u(j) = 1$, if R^j has at least one connected client; $u(j) = 0$, if R^j has no connected client. And an upper bound is also obtained for the worst case of per client throughput:

12	6	10	8	5
3	6	6	10	9
9	10	7	8	11
10	9	5	9	9
8	8	8	4	10

(a)

159	202	215	210	162
201	261	284	266	218
222	293	316	302	237
212	265	293	275	217
160	206	212	202	165

(b)

Figure 5. An example of multi-hop traffic-flow weight

$$\begin{aligned} \min_i TH(i, N_g) &\le \min_i TH_{W_2}(i) \\ &= \min_j \frac{c_2 W_2}{CRF \times N_c(j)} \\ &= \frac{c_2 W_2}{CRF \times \max_j N_c(j)}. \end{aligned}$$

The above upper bounds are independent of N_g. Actually they are the maximal value that $\sum_{i=1}^{N_c} TH(i, N_g)$ and $\min_i TH(i, N_g)$ can achieve for any number of gateways.

4. MULTI-HOP TRAFFIC-FLOW WEIGHT GATEWAY PLACEMENT ALGORITHM

Adding new gateways can increase throughput in backbone communications by effectively reducing the average number of hops each packet needs to access to gateways and reducing the traffic load on existing gateways. However, the above benefits may be dramatically mitigated by careless gateway placement since new gateways may also introduce more interference to existing gateways. Therefore, a good gateway placement algorithm can maximally relief traffic load in the network but introduce minimal interference.

A good gateway placement algorithm should also be adaptive to the deployed number of gateways. A relative small number of deployed gateways means large number of hops a packet needs to access to gateways, in which case huge traffic load results from packets' long distance traveling in the network. Therefore, geometry-balanced placement algorithms, e.g. regular placement, may achieve good results since they can effectively reduce the average number of hops. In the opposite case, when a relatively large number of gateways are planned to deploy, placing the gateways in the areas with the most traffic load may be simply the best solution.

In this section, an innovative gateway placement algorithm is introduced, which has all the above-mentioned benefits.

4.1 Adaptive multi-hop traffic-flow weight

A traffic-flow weight, denoted as $MTW(j)$, is calculated on the mesh router R^j, $j = 1 \ldots N_r$. Each time a new gateway will be placed on the router with the highest weight. The weight computation is adaptive to the following factors: 1) the number of mesh routers and the number of gateways, i.e., N_r and N_g; 2) traffic demands from mesh clients; 3) the location of existing gateways in the network; 4) The interference from existing gateways. Factors 1) to 3) will be discussed in this subsection and factor 4) will be presented in the next subsection.

In the first step of the algorithm, a variable called weight of hops' number, denoted as W_{hop}, is decided. W_{hop} is a function of N_r and N_g, and is given as follows:

$$W_{hop} = round\left(\frac{\sqrt{N_r}}{2\sqrt{N_g}}\right) . \tag{5}$$

W_{hop} can be considered as an estimation on the average number of hops that a packet needs to travel from a gateway to a mesh router.

In the second step, local traffic demand on each mesh router, denoted as $D(j), j = 1...N_r$, is calculated. $D(j)$ displays the traffic demand from all the mesh clients connected to R^j. In our WMN model, all mesh clients are equivalent. Therefore, the number of mesh clients connected to R^j is used as $D(j)$. Figure 5(a) shows an example of $D(j)$ when 200 mesh clients are uniformly distributed and 25 mesh routers are placed on a 5-by-5 regular grid.

In the third step, $MTW(j)$ is calculated with $D(j)$ and W_{hop} as follows:

$$\begin{aligned} MTW(j) = {} & (W_{hop}+1)\times D(j) \\ & +W_{hop}\times(\text{traffic demand on all 1-hop neighbors of } R^j) \\ & +(W_{hop}-1)\times(\text{traffic demand on all 2-hop neighbors of } R^j) \\ & +(W_{hop}-2)\times(\text{traffic demand on all 3-hop neighbors of } R^j) \\ & +... \end{aligned}$$

Please note that negative items are not counted in the above formula. With $MTW(j)$, the first gateway will be placed on the router with the highest weight. In the next step, $D(j), j = 1...N_r$ will be re-adjusted with W_{hop}. Assuming that the gateway is placed at R^j, the traffic demand value of R^j and all its neighbors within $(W_{hop}-1)$ hops away will be set as 0, and the value of R^j's W_{hop} hops neighbors will be reduced to half. In this way, the other gateways are less likely to be placed in a location near the existing gateways.

Figure 5(b) demonstrates an example that how $D(j)$ and W_{hop} are combined to affect gateway placement. Figure 5(b) is an example of *MTW*, which is calculated using $D(j)$ as depicted in Figure 5(a) and $W_{hop} = 3$. From (5), we know that in this case $N_g = 1$. So there is only one gateway being deployed and it will be placed in the center of the WMN. In the next subsection, interfere among gateways will also be counted in the computation of *MTW*.

4.2 Optimal sharing efficiency of gateways

It is assumed that two gateways interfere with each other if they are within the distance of *IntD*-hops in backbone

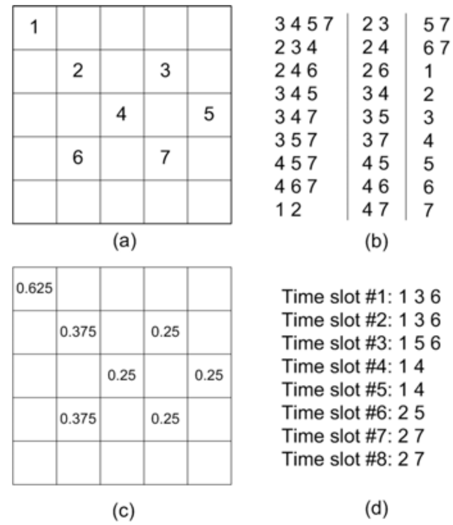

Figure 6. Obtaining the optimal sharing efficiency on gateways with $IntD = 2$

communications. *IntD* is defined as *Interfering Distance of gateways*. In the first step, *table of interfering gateways* is constructed by the steps as follows: 1) each gateway appears as a single line in the table; 2) except the above lines, all the lines contain more than one gateways representing all possible combination such that in each line, any two gateways interfere with each other; 3) The line with more gateways always appears in the higher position in the table. For example, seven gateways are deployed on a 5-by-5 mesh backbone grid, as shown in Figure 6(a) and its table of interfering gateways is displayed in Figure 6(b), here $IntD = 2$.

In the second step, each gateway is assigned a percentage number in the procedures as follows: 1) initially all gateways are assigned with a value of 100%; 2) the table of interfering gateways is searched from the top line to the last line with more than one gateway at a speed of one line per step; 3) in each step, all gateways in a specific line are split into 2 groups by threshold value of (1 / the number of gateways in the line). The first group contains the gateways with larger value than the threshold value and the second group has the rest of the gateways in this line; 4) all gateways in the first group will be re-assigned a new percentage value calculated as follows:

$$\frac{1-\text{sum of all the percentage value in the second group}}{\text{the number of the gateways in the first group}};$$

5) the procedures of 3) and 4) repeat until finish. In the example shown in Figure 6, gateway 3, 4, 5 and 7 are re-assigned a percentage value of 25% in the computation of the first line; gateway 2 is re-assigned a percentage value of 50% in the computation of the second line; gateway 2 and 6 are re-assigned a percentage value of 37.5% in the computation of the third line; gateway 1 is re-assigned a percentage value of 62.5% in the computation of the ninth line. The final results are shown in Figure 6 (c).

The optimal traffic scheduling scheme on gateways is constructed. In the scheme, time slots in backbone communications are assigned to all gateways such that successful simultaneous transmissions can be always carried out in each time slot. And each gateway can be guaranteed to have a number of time slots, which is equal to the total number of all time slots times the percentage value obtained in the previous step. Figure 6 (d) shows an example of such a TDMA scheme. The above percentage value assigned to a gateway is defined as the optimal sharing efficiency for the specific gateway, denoted as $G_{eff}(k),\ k = 1...N_g$.

Finally, adding a new gateway into the network with the presence of existing gateways will have the following procedures: 1) from previous steps, choosing the router with the highest weight as a potential location for gateway placement; 2) adding the potential location into the existing table of interfering gateways and re-constructing the table; 3) computing the sharing efficiency for the potential gateway location by the new table of interfering gateways; 4) Re-adjusting the highest weight by timing the sharing efficiency, i.e., $MTW'(j) = MTW(j) \times G_{eff}(j)$; 5) if the new weight is still larger than the second highest weight, then place the gateway in the location. Otherwise, repeat the above steps from 2) to 5) until obtaining the location.

4.3 Other gateway placement algorithms

The above proposed algorithm (MTWP) will be compared with the following three gateway placement algorithms:

- *Random Placement* (RDP): N_g gateways choose their placement location randomly on N_g mesh routers
- *Busiest Router Placement* (BRP): N_g gateways choose their placement location on the N_g mesh routers with the highest traffic demand defined by $D(j),\ j = 1...N_r$.
- *Regular Placement* (RGP): as many as possible gateways are placed based on regular patterns and the rest of them choose their placement location on the same number of mesh routers with the highest traffic demand defined by $D(j),\ j = 1...N_r$. Table 1 gives an example of RGP on a 6-by-6 regular grid.

5. NUMERIC RESULTS AND DISCUSSION

Using the framework of throughput computation defined in Section 3, throughput of the WMN is studied by simulations in this section. In all the simulations, we assume $N_c = 200$, $N_r = 36$, and $l = 1000m$, i.e. there are 200 mesh clients distributed in a square region of $1000m \times 1000m$; the square is split evenly into 36 small square cells and a mesh router is placed in the center of each cell. In addition, we assume $CRF = 4$, and $SRD = 3$, and $IntD = 2$. A certain number of gateways will be placed on the top of the best-fit mesh routers based on a certain placement algorithm. Since mesh clients in all cases follow a random distribution, the results in all plots are obtained as an average over 200 iterations.

Table 1. An example of RGP on a 6-by-6 regular grid

N_g	**Gateway Placement**
1	Choose the busiest router from the location of (3,3), (3,4), (4,3), (4,4)
2~4	Choose the N_g busiest routers from the location of (2,2), (2,5), (5,2), (5,5)
5~7	Choose the first 4 gateways at the location of (2,2), (2,5), (5,2), (5,5) and choose the rest on the other routers with the highest traffic demand
8	36 routers are split into 4 groups. In each group, any two routers are at least 2-hops away, e.g. (1,1), (1,3), (1,5), (3,2), (3,4), (3,6), (5,1), (5,3), (5,5) are in one group. Choose the first gateway on the busiest router and choose the rest 7 gateways on the next 7 busiest routers in the same group with the first one.
≥ 9	36 routers are split into 4 groups as above. Choose the first gateway on the busiest router, then choose the next 8 gateways on the other routers in the same group with the first one and choose the rest on the other routers with the highest traffic demand

In the first case, we study the relationship between channel capacity of mesh routers and the number of gateways. We assume that all mesh clients are uniformly distributed and each of them can transmit at 10Mbps in downlink communications, i.e., $c_2 W_2 = 10Mbps$. The aggregate throughput of the WMN versus the number of gateways is shown in Figure 8, where gateways are placed by the proposed MTWP algorithm and the channel capacity of mesh routers varies from 10Mbps to 25Mbps with an increment of 5Mbps. Our results confirms the fact that the number of gateways can be dramatically reduced by using more powerful mesh routers in the backbone, e.g. 6 gateways with mesh router transmitting at 25Mbps can achieve much better throughput performance than 15 gateways with mesh router transmitting at 10Mbps.

In the second case, as shown in Figure 9 and Figure 10, we compare throughput performance of 4 gateway placement algorithms in the WMN. We assume that all mesh clients are uniformly distributed and each mesh client and mesh router can transmit at 10Mbps and 20Mbps, respectively. The results show that the proposed MTWP algorithm clearly outperforms the other algorithms in both the aggregate throughput and the worst case throughput. The regular placement algorithm achieves the second best results because it is a geometry-balanced algorithm which can effectively reduce the average distance between a gateway and its associated mesh routers.

In the third case, as shown in Figure 11 and Figure 12, we compare throughput performance of 4 gateway placement algorithms when mesh clients are distributed unevenly in the network, as depicted in Figure 7. Please note that in each of the 9 regions in Figure 7, nodes are still uniformly distributed, however, nodes density is very different among the 9 regions. In this case, MTWP algorithm outperforms the other 3 algorithms in every single case. Here we double the channel capacity of mesh clients assuming mesh clients and mesh routers can both transmit at 20Mbps. Otherwise, improvements by gateway placement algorithms may not be observed since very low throughput of

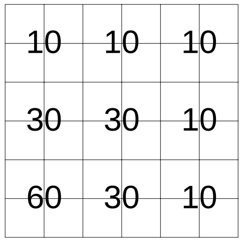

Figure 7. An example uneven nodes' distribution

local communications becomes the major constraint for throughput performance of the whole WMN, which results from very high nodes' density in some regions.

In both the second and third cases, as shown in Figure 9-12, the MTWP algorithm has the biggest improvement on the throughput when the number of gateways is chosen from 5 to 8. An explanation is given as follows: with more than 4 gateways in a 6-by-6 grid backbone network, gateways start to interfere with each other. Comparing with the other 3 algorithms, MTWP algorithm has a unique mechanism to mitigate such interference among gateways. Thus, countering interference among gateways is very critical for a gateway placement algorithm.

6. CONCLUSION

The problem of optimal gateway placement for throughput in WMNs has been investigated. In a typical WMN model, successful simultaneous transmissions can always be guaranteed by TDMA scheduling schemes. Upon the above scheduling, throughput computation in WMNs has been carried out to verify the performance of the proposed gateway placement algorithm. In the algorithm, gateway placement is decided by a comprehensive traffic weight calculation. Numerical results illustrated the proposed algorithm achieved much better performance than other schemes.

7. ACKNOWLEDGMENTS

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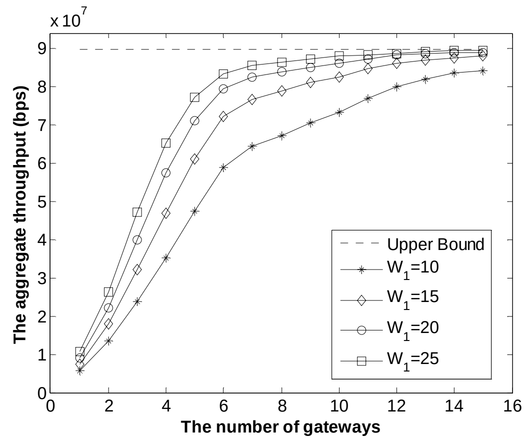

Figure 8. The aggregate throughput by changing the number of gateways with different channel capacity of mesh routers

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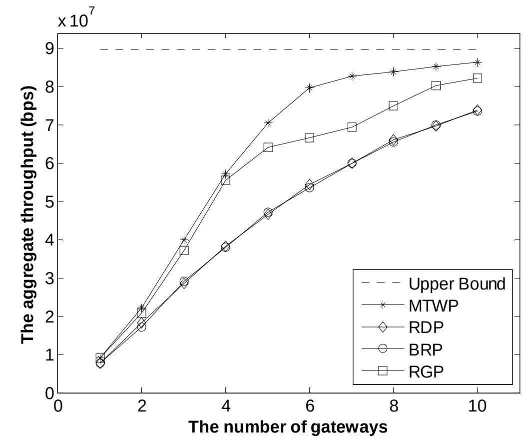

Figure 9. The comparison of the aggregate throughput with uniformly distributed mesh clients

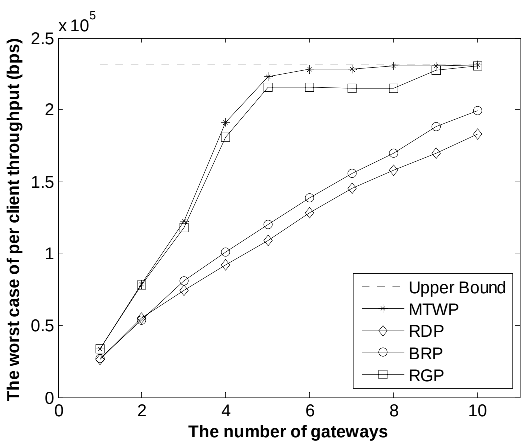

Figure 10. The comparison of the worst case of per client throughput with uniformly distributed mesh clients

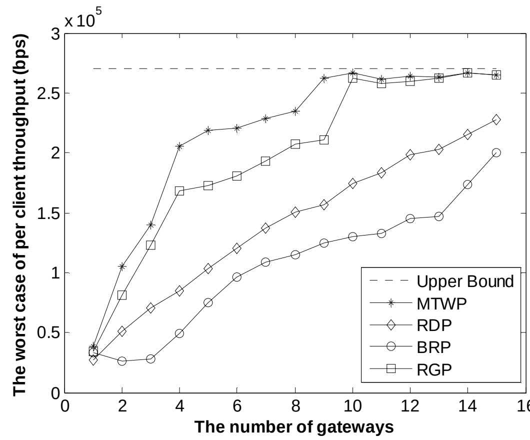

Figure 11. The comparison of the aggregate throughput with unevenly distributed mesh clients

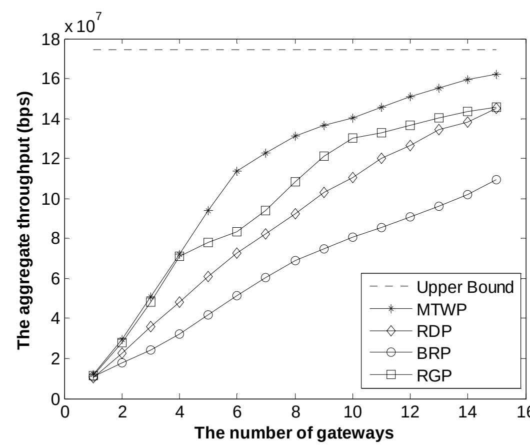

Figure 12. The comparison of the worst case of per client throughput with unevenly distributed mesh clients