Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2010, Article ID 368423, 12 pages
doi:10.1155/2010/368423

Research Article

On Optimizing Gateway Placement for Throughput in Wireless Mesh Networks

Ping Zhou,[1] Xudong Wang,[2] B. S. Manoj,[3] and Ramesh Rao[3]

[1] *QCT Modem Technology Systems, Qualcomm, Inc., San Diego, CA 92121, USA*
[2] *UM-SJTU Joint Institute, Shanghai Jiao Tong University, Shanghai 200240, China*
[3] *Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093, USA*

Correspondence should be addressed to Xudong Wang, wxudong@ieee.org

Received 4 November 2009; Accepted 24 February 2010

Academic Editor: Xinbing Wang

An innovative gateway placement scheme is proposed for wireless mesh networks (WMNs) in this paper. It determines the location of a gateway based on a new performance metric called multihop traffic-flow weight (MTW). The MTW computation takes into account many factors that impact the throughput of WMNs, that is, 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. Thus, the proposed gateway placement scheme provides a framework of significantly improving throughput of WMNs through proper placement of gateways. To evaluate the performance of the new gateway placement scheme, a nonasymptotic throughput of WMNs is derived by considering TDMA scheduling. The derivations also provide a guideline for designing scheduling schemes of WMNs. Numeric results show that the proposed gateway placement scheme constantly outperforms other schemes by a large margin.

1. Introduction

A wireless mesh network (WMN) consists of mesh routers and mesh clients. Mesh routers form an infrastructure network, called mesh backbone, to support the network access of mesh clients. They are powerful devices without constraints of energy, computing power, and memory and are usually 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, for example, 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, gateway placement is one of the most challenging but problem. There are some analogous research results in wired or cellular networks. For example, a number of studies have been carried out to place web proxies or server replicas to optimize clients' performance [2–4]. Another example is the base station placement problem in cellular networks [5–7]. However, when wireless links replace wired links and multi-hop communications replace single-hop communications, a more comprehensive traffic modeling scheme is required to solve the backbone nodes placement problem in multi-hop wireless networks. More recently, Bejerano [8] studied gateway placement in multi-hop wireless networks where network nodes were partitioned into minimal number of disjoint clusters that satisfied throughput and delay constraints. Various gateway or backbone nodes placement algorithms were proposed for WMNs [9–12]. However, all the above investigation has been focused on network connectivity of WMNs by deploying the minimum number of backbone nodes.

Throughput is one of the most critical parameters that ensure the services of WMNs to meet the requirements of

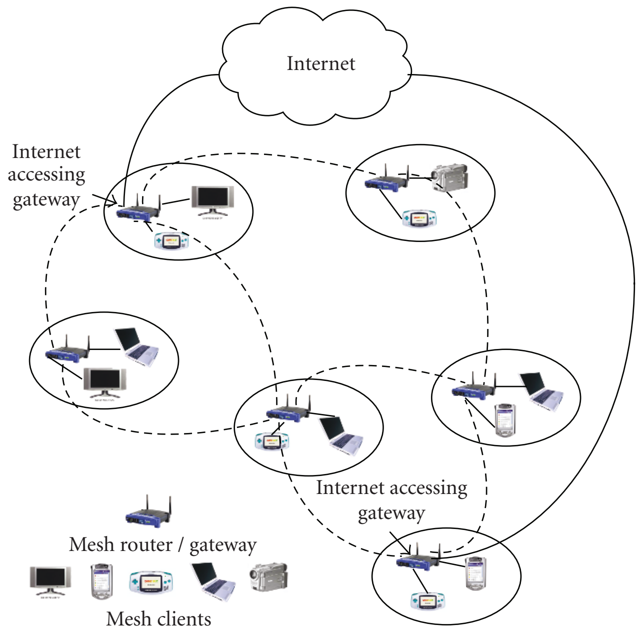


Figure 1: A typical WMN.

customers. Unlike all the above research work, in this paper, given a certain number of gateways, we aim to develop a gateway placement algorithm to significantly enhance throughput performance of WMNs. A very similar problem was addressed in [13], but in that study gateway locations are either prefixed or searched on a preselected grid in a brutal-force way. Moreover, uneven distributed traffic demand has not been studied. In our paper, optimal gateway locations can be quickly chosen by an intelligent algorithm, which applies for all the traffic distribution scenarios.

To develop a throughput-oriented gateway placement algorithm, we first 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 colocate with the mesh router that has the highest MTW.

To evaluate the performance of the MTW-based gateway placement scheme, a throughput computation model needs to be derived. However, throughput analysis of wireless networks is an extremely challenging research topic. Throughput capacity of multi-hop wireless networks has been studied in other papers. Gupta and Kumar [14, 15] 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 [16]. The capacity of hybrid ad hoc networks was investigated in [17–19]. All such results of throughput analysis 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. The work of asymptotic analysis on the capacity of WMNs has been initiated in [20] where asymptotic throughput results are obtained by assuming that the size of the network goes to infinity. Since real networks always have limited size, these asymptotic results provide very limited information for practical network design. Thus, in this paper a nonasymptotic analytical model is derived to calculate the throughput of WMNs. TDMA scheduling is assumed to coordinate packet transmissions in mesh clients, mesh routers, and gateways.

Numerical results based on the throughput computation model show that the new gateway placement algorithm greatly enhances the throughput performance of WMNs. Comparison study is also carried out in this paper to compare the proposed scheme with other schemes such as random placement, regular placement, and busiest router placement. Results illustrate that our proposed gateway placement algorithm outperforms all these schemes by a large margin.

The rest of this paper is organized as follows. In Section 2, a typical WMN model is described and two throughput metrics for gateway placement are formulized. The new gateway placement algorithm is proposed in Section 3, while the throughput computation model needed by this algorithm is derived in Section 4. The numeric results are obtained in Section 5 to evaluate the performance of the proposed algorithm. 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 $R_s^j = [0, l_s]^2$ ($j = 1 \cdots (l/l_s)^2$), 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 follows, we will limit the case of interests to that where $1 < N_r \leq N_c$, that is, there are more than one mesh routers and 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; that is, 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 is expected to 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 $1 \leq N_g \leq N_r$; that is, the number of gateways cannot exceed the number of mesh routers. We chose the square grid topologies mainly because the recent studies on the deployment issues [21] have shown that square grid topologies are more realistic in delivering the desired network performance.

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

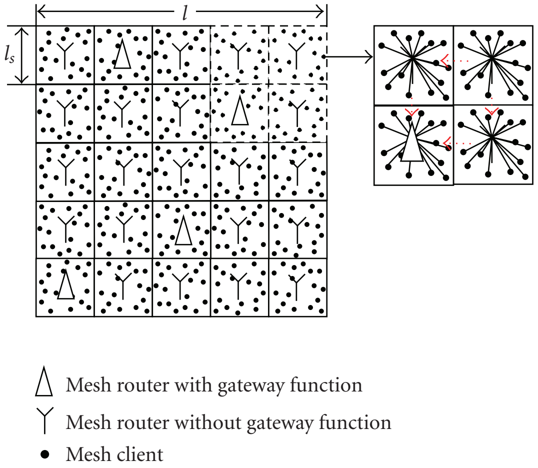


Figure 2: Network topology of an infrastructure WMN with gateways.

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. 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 router will load its traffic to all its nearest gateways by round robin. A mesh client is said to be associated with a gateway if its connected router is associated with the gateway. Hence, traffic load of a mesh client will also be shared by all its potentially associated gateways.

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

(i) *Local communications*: it is referred as the communications between a mesh router and a mesh client.

(ii) *Backbone communications*: it is referred as the communications between two mesh routers, which includes the communications between a gateway and a mesh router.

(iii) *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.

(iv) *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. To help elaborate the new gateway placement scheme and its throughput computation, a transmission model is specified as follows.

Each mesh router is equipped with two radio interfaces: one transmitting at W_1 bits/s for backbone communications and the other transmitting at W_2 bits/s for 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. It should be noted the two radio interfaces of a mesh router can be two physical radio interfaces or two virtual radio interfaces. In the later case, only one physical radio interface is needed for a mesh router and switching channels in time slots for backbone or local communications achieves two virtual interfaces.

Moreover, mesh routers can receive packets from only one sender at a time. The same constraint is imposed on mesh clients. Transmission and reception can occur in either time-division duplex (TDD) or frequency division duplex (FDD), depending on how the physical and MAC layers are implemented.

In either local communications or backbone communications, simultaneous transmissions are coordinated by the Protocol Model as defined in [14]; that is, if a transmission from node S_i to S_j is successful, then the following conditions must be satisfied: (1) $|S_i - S_j| \leq r_i$; (2) for every other transmitting node S_k, $|S_k - S_j| \geq (1+\Delta)r_k$, 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. Throughput. In order to evaluate the performance of gateway placement algorithms, the aggregate throughput and the worst-case per-client throughput need to be derived. In this subsection, two problems of throughput maximization are formulized, which leads to the definitions of two throughput metrics. The actual framework of computing the nonasymptotic value of these throughput metrics will be provided in Section 4.

Problem 1. Optimal gateway placement for maximizing aggregate throughput of WMNs, that is, 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

$$\sum_{i=1}^{N_c} \mathrm{TH}\left(i, N_g\right) \tag{1}$$

is maximized, where $\mathrm{TH}(i, N_g)$ denotes the per-client throughput of the ith mesh client when N_g gateways are deployed.

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

$$\min_{i=1}^{N_c} \mathrm{TH}\left(i, N_g\right) \tag{2}$$

is maximized.

3. Multihop Traffic-Flow Weight Gateway Placement

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 can dramatically diminish due to inappropriate gateway placement, since new gateways will also result in more interference to existing gateways. Therefore, the best gateway placement algorithm should not only relieve traffic load in the network but also introduce minimal interference.

In general a gateway placement scheme must be adaptive to the deployed number of gateways. A relative small number of deployed gateways mean a large number of hops that a packet needs to traverse to gateways, which results in huge traffic load. Therefore, geometry-balanced placement algorithms, for example, regular placement, may achieve fairly 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 for deployment, 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 proposed. It holds all the above-mentioned benefits. In the algorithm, a traffic-flow weight, denoted by $\text{MTW}(j)$, is calculated iteratively on the mesh router R^j, $j = 1 \cdots N_r$. 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, that is, N_r and N_g; (2) traffic demands from mesh clients; (3) the location of existing gateways in the network; and (4) the interference from existing gateways. How factors (1) to (3) are captured in MTW will be discussed in Section 3.1, and the relationship between factor (4) and MTW will be discussed in Section 3.2. The MTW-based gateway placement algorithm will be explained while the MTW is derived in Sections 3.1 and 3.2.

3.1. Adaptive Multihop Traffic-Flow Weight. In the first step of the algorithm, a variable called *gateway radius*, denoted by R_g, is decided. R_g is the number of hops from a gateway to its farthest mesh router. In this paper, (1) is used to estimate R_g:

$$R_g = \text{round}\left(\frac{\sqrt{N_r}}{2\sqrt{N_g}}\right). \tag{3}$$

The rationale of this estimation can be explained as follows. Considering that a square is divided equally by N_r cells and N_g cells, respectively, then drawing a horizontal line across the square will statistically meet $\sqrt{N_r}$ cells and $\sqrt{N_g}$ cells. For each N_g-cell, the line will cross $\sqrt{N_r}/\sqrt{N_g}$ N_r-cells. Therefore, if a gateway is placed in the center of each N_g-cell and a mesh router is placed in the center of each N_r-cell, we can estimate that a gateway needs $\sqrt{N_r}/2\sqrt{N_g}$ hops to reach its farthest mesh router. It should be noted that (1) only provides an estimation, which may not be always precise for every combination of N_r and N_g.

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 3: An example of multi-hop traffic-flow weight.

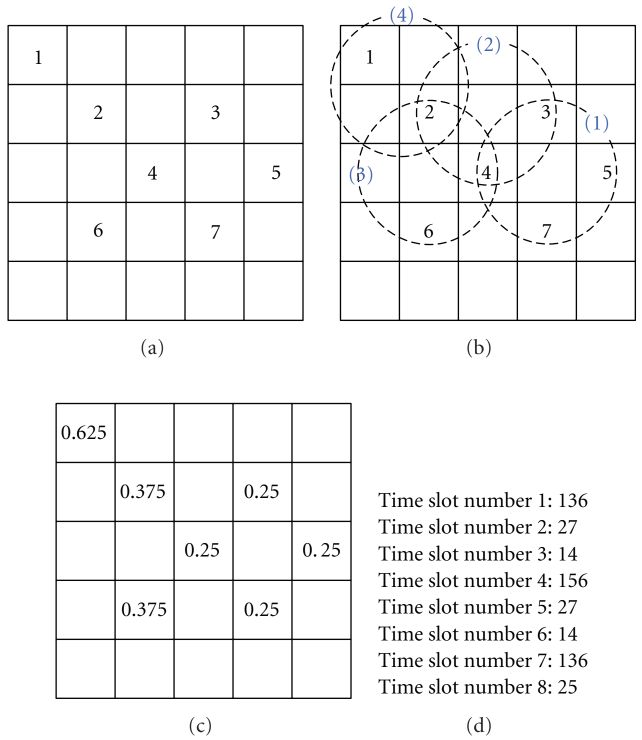
In the second step, local traffic demand on each mesh router, denoted by $D(j)$, $j = 1 \cdots N_r$, is calculated. Since $D(j)$ is actually the traffic demand from all the mesh clients connected to R^j and all mesh clients are assumed to be equivalent in our WMN model, $D(j)$ can be represented by the number of mesh clients connected to R^j. Figure 3(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, $\text{MTW}(j)$ is calculated with $D(j)$ and R_g as follows:

$$\begin{aligned}
&\text{MTW}(j)\\
&= \left(R_g + 1\right) \times D(j)\\
&\quad + R_g \times \left(\text{traffic demand on all 1} - \text{hop neighbors of } R^j\right)\\
&\quad + \left(R_g - 1\right) \times \left(\text{traffic demand on all 2} - \text{hop neighbors of } R^j\right)\\
&\quad + \left(R_g - 2\right) \times \left(\text{traffic demand on all 3} - \text{hop neighbors of } R^j\right)\\
&\quad + \cdots .
\end{aligned} \tag{4}$$

With $\text{MTW}(j)$, the first gateway will be placed on the router with the highest weight. An example in Figure 3 shows how $D(j)$ and R_g are combined to determine gateway placement according to MTW. In this example, there is only one gateway to be deployed, so $N_g = 1$. From (3), we have $R_g = 3$. Therefore, based on $D(j)$ in Figure 3(a), the MTW is calculated as shown in Figure 3(b). Therefore, the gateway will be placed in the center mesh router of the WMN that has the highest MTW weight.

If more than one gateway is to be placed, two additional steps are needed. Firstly, $D(j)$, $j = 1 \cdots N_r$ will be readjusted with R_g. Assuming that the gateway is placed at R^j, the traffic demand value of R^j and all its neighbors within $(R_g - 1)$ hops away will be set as 0, and the value of R^j's R_g-hop neighbors will be reduced to half. In this way, another gateway is less likely to be placed in a location near the existing gateway. Secondly, interfere among gateways should be counted in the computation of MTW, as discussed in the next subsection.



Time slot number 1: 136
Time slot number 2: 27
Time slot number 3: 14
Time slot number 4: 156
Time slot number 5: 27
Time slot number 6: 14
Time slot number 7: 136
Time slot number 8: 25

(a) (b) (c) (d)

Figure 4: Obtaining the optimal sharing efficiecy on gateways.

3.2. Sharing Efficiency of Gateways. Two gateways interfere with each other if they are within the distance of Int D-hops. Int D is defined as *Interfering Distance of gateways*. Interfering gateways have to share the same wireless channel in the backbone communications. An algorithm is developed in this subsection to derive the sharing efficiency of gateways. The algorithm holds the two distinct features: (1) full fairness among gateways will be guaranteed; (2) under the condition of (1), the efficiency for each gateway will be maximized.

In the first step, the table of *nonoverlapping interfering groups* is constructed as follows: (1) each interfering group appears as a single row in the table and contains a set of gateways, any two of which interfere with each other; (2) the group with more gateways always has a smaller row number, that is, it appears earlier in the table; (3) a group appearing later must have at least one gateway that is not included by all the previous groups. For example, seven gateways deployed on a 5-by-5 mesh backbone grid are shown in Figure 4(a). When Int $D = 2$, the corresponding table of nonoverlapping interfering groups is illustrated in Figure 4(b) and listed in Table 1.

In the second step, each gateway is assigned a percentage value according to the following procedure. (1) Initially all gateways are assigned with a value of 100%. (2) The table of non-overlapping interfering groups is searched from the top row to the last row at a pace of one row per step. (3) In each step, all gateways in a specific row are split into 2 groups by a threshold value of (1/the number of gateways in the row). The first group contains the gateways with a larger value than the threshold and the second group contains the rest of the gateways in this row. (4) All gateways in the first group will then be reassigned a new percentage value calculated as

$$\frac{1 - \text{sum of all the percentage value in the second group}}{\text{the number of the gateways in the first group}}, \tag{5}$$

if the new one is smaller than its current value. (5) The procedures of (3) and (4) are repeated until the end. In the example shown in Figure 4 and Table 1, gateways 3, 4, 5, and 7 are reassigned a percentage value of 25% in the computation of the first row; gateway 2 is reassigned a percentage value of 50% in the computation of the second row; gateways 2 and 6 are reassigned a percentage value of 37.5% in the computation of the third row; gateway 1 is reassigned a percentage value of 62.5% in the computation of the fifth row. The final results are shown in Figure 4(c).

The final percentage value assigned to each gateway in the above algorithm is defined as the optimal sharing efficiency, denoted by $G_{\text{eff}}(k)$, $k = 1 \cdots N_g$, because, firstly, it guarantees a full fairness among all the gateways, and secondly it always guarantees the existence of a traffic scheduling scheme for all the gateways, since in each interfering group, the sum of the sharing efficiency is always equal or smaller than 100%. In the scheduling 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. Each gateway can be guaranteed to have a number of time slots, which is equal to the total number of time slots multiplying the sharing efficiency. Figure 4(d) shows a TDMA scheduling scheme for the above example.

By taking into account the interference of gateways via the sharing efficiency, a new gateway can be placed into the network with the following procedures: (1) from previous steps in Section 3.1, choosing the router with the highest weight as a potential location for gateway placement; (2) reconstructing the table of non-overlapping interfering groups by adding the potential location into the consideration; (3) computing the sharing efficiency for the potential gateway location; (4) readjusting the highest weight by multiplying the sharing efficiency, that is, $\text{MTW}'(j) = \text{MTW}(j) \times G_{\text{eff}}(j)$; and (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 (1) to (5) until obtaining the location.

4. Traffic Scheduling for Throughput Computation

In this section, a TDMA scheme is applied for traffic scheduling. One key benefit of using TDMA is that it guarantees collision free transmissions. In fact, various TDMA scheduling schemes are actually used in a few wide area wireless mesh network testbeds and network standards such as WiMAX. Based on TDMA scheduling, we provide a framework of non-asymptotic throughput derivation for WMNs.

The WMN model indicates that all wireless mesh routers contend for the same wireless channel of capacity W_1 in

Table 1: Optimal sharing efficiency calculation.

Row no.	Non-overlapping interfering group	Sharing efficiency						
		1	2	3	4	5	6	7
		100%	100%	100%	100%	100%	100%	100%
(1)	3 4 5 7	100%	100%	**25**%	**25**%	**25**%	100%	**25**%
(2)	2 3 4	100%	**50**%	25%	25%	25%	100%	25%
(3)	2 4 6	100%	**37.5**%	25%	25%	25%	**37.5**%	25%
(4)	1 2	**62.5**%	37.5%	25%	25%	25%	37.5%	25%

backbone communications, and all mesh routers and mesh clients contend for capacity W_2 in local communications. Therefore, the throughput of the ith mesh client when N_g gateways are deployed, denoted by $\mathrm{TH}(i, N_g)$, is generally constrained by both W_1 and W_2. Since W_1 and W_2 are orthogonal, $\mathrm{TH}(i, N_g)$ can be obtained by computing the throughput constrained by W_1 and the throughput constrained by W_2 separately, that is,

$$\begin{aligned}&\mathrm{TH}\left(i, N_g\right)\\&\quad= \min\left\{\mathrm{TH}_{W_1}\left(i, N_g\right), \mathrm{TH}_{W_2}(i)\right\}, \quad i = 1 \cdots N_c.\end{aligned} \tag{6}$$

Here $\mathrm{TH}_{W_1}(i, N_g)$ is defined as the throughput of the ith mesh client in backbone communications when there are N_g gateways in the WMN and $\mathrm{TH}_{W_2}(i)$ is defined as the throughput of the ith mesh client in local communications. Note that $\mathrm{TH}_{W_2}(i)$ is independent of N_g in the WMN model. (2) indicates that a feasible per-client throughput can be achieved by taking the smaller one of $\mathrm{TH}_{W_1}(i, N_g)$ and $\mathrm{TH}_{W_2}(i)$.

Since W_1 and W_2 should be split for uplink and downlink communications, respectively, it is assumed that $c_1 W_1$ and $c_2 W_2$ 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 $c_1 W_1$ and $c_2 W_2$. This is not an uncommon case in today's applications of WMNs, for instance, in the application of Internet access. We shall note that the methodology proposed in this section can actually be used to obtain throughput of WMNs when both uplink traffic and downlink traffic are present. However, with the above simplified model, we can focus on the illustration of the key ideas without being distracted by trivial discussions.

4.1. 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 with full fairness; (2) under the condition of (1), each gateway should have as much as possible time slots for successful transmissions. In Section 3.2, an algorithm to obtain the optimal sharing efficiency on all the gateways, denoted by $G_{\mathrm{eff}}(k)$, $k = 1 \cdots N_g$, is provided and 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 $G_{\mathrm{eff}}(k)$. Hence, the kth gateway is guaranteed to have an aggregate throughput of $G_{\mathrm{eff}}(k) \times c_1 W_1$ in backbone communications. By the TDMA scheme, interfering gateways share the same wireless channel while noninterfering 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, that is, $\mathrm{TH}_{W_1}(i_1, N_g) = \mathrm{TH}_{W_1}(i_2, N_g)$, 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 located $N_{\mathrm{hop}}(j)$ hops away from its associated gateway. The second property requires that R^j be assigned $N_C(j) \times N_{\mathrm{hop}}(j)$ small time slots if there are no simultaneous transmissions along the way from the gateway to R^j. Figure 5. 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 5. Therefore, the actual time slot that an R^j-connected mesh client needs to meet the second property, denoted by $N'_{\mathrm{hop}}(j)$, has the following relationship with $N_{\mathrm{hop}}(j)$:

$$\begin{aligned}N'_{\mathrm{hop}}(j) &= N_{\mathrm{hop}}(j), \quad \text{if } N_{\mathrm{hop}}(j) < \mathrm{SRD};\\N'_{\mathrm{hop}}(j) &= \mathrm{SRD}, \quad \text{if } N_{\mathrm{hop}}(j) \geq \mathrm{SRD}.\end{aligned} \tag{7}$$

With the first property all mesh clients associated with a specific gateway require total $\sum_l (N_C(l) \times N'_{\mathrm{hop}}(l))$ small time slots for "interference free" transmissions in backbone communications. Hence, the kth gateway can guarantee the

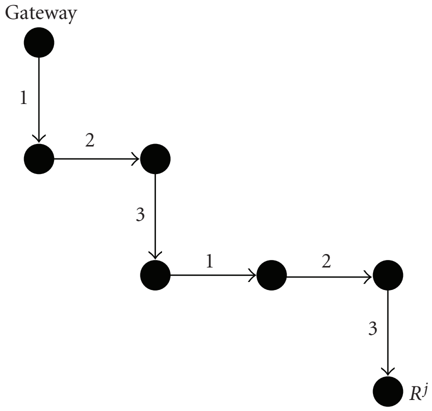


Figure 5: A TDMA scheduling scheme in backbone communications with SRD = 3.

following per-client throughput for all its associated mesh clients in backbone communications:

$$\mathrm{TH}_g(k)=\frac{G_{\mathrm{eff}}(k)\times c_1W_1}{\sum_{\substack{l=\text{all associated routers}\\ \text{with the } k\text{th gateway}}}\left(N_C(l)\times N'_{\mathrm{hop}}(l)\right)}. \tag{8}$$

With the consideration that a mesh router may have more than one potentially associated gateways and it will use all these gateways by round robin for fairness, the mesh router will assign all its time slots equally to its associated gateways. Therefore, the per-client throughput on the kth gateway can be modified to

$$\mathrm{TH}'_g(k)=\frac{G_{\mathrm{eff}}(k)\times c_1W_1}{\sum_{\substack{l=\text{all associated routers}\\ \text{with the } k\text{th gateway}}}\left(N_C(l)\times N'_{\mathrm{hop}}(l)\div N_g(l)\right)}, \tag{9}$$

where $N_g(l)$ denotes the number of the associated gateways with the mesh router R^l.

Assuming that the ith mesh client is connected with the mesh router R^j, finally, the per-client throughput of the ith mesh client in backbone communications is the averaged throughput over all its associated gateways:

$$\mathrm{TH}_{W_1}\left(i,N_g\right)=\frac{\sum_{\substack{k=\text{all the associated gateways}\\ \text{with the mesh router } R^j}}\mathrm{TH}'_g(k)}{N_g(j)}. \tag{10}$$

An example is illustrated in Figure 6 for the throughput computation in backbone communications. In the example, there are 5 mesh routers, 2 of which are also gateways, denoted by G^1 and G^2. It is assumed that both gateways have 50% sharing efficiency and all the mesh routers have 10 mesh clients. In the model, the mesh routers R^1 and R^3 are associated with G^1 and G^2, respectively; R^2 is associated with both G^1 and G^2 and it uses both the gateways by round robin. Thus, we have

$$\begin{gathered}N_C(1)=N_C(2)=N_C(3)=10,\\ N'_{\mathrm{hop}}(1)=N'_{\mathrm{hop}}(2)=N'_{\mathrm{hop}}(3)=1,\\ N_g(1)=N_g(3)=1,\quad N_g(2)=2.\end{gathered} \tag{11}$$

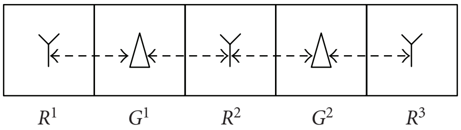


Figure 6: An example of traffic scheduling in backbone communications.

By (9), we obtain

$$\mathrm{TH}'_g(1)=\mathrm{TH}'_g(2)=\frac{0.5c_1W_1}{15}=\frac{c_1W_1}{30}. \tag{12}$$

Finally, by (10), we obtain that each of the 30 mesh clients associated with R^1, R^2, and R^3, respectively, can achieve throughout of $c_1W_1/30$ bp sin the backbone communications.

The TDMA traffic scheduling scheme actually guarantees the full fairness among mesh clients for each gateway. Note that farther mesh clients from gateways are reserved more time slots for transmission so that their throughput is not throttled by closer ones.

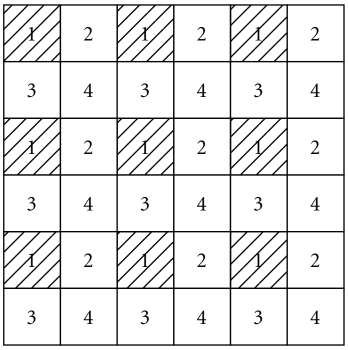
The per-client throughput in backbone communications will be compared with the per-client throughput in local communications to decide the per-client throughput in the WMN. Note that if a mesh client is connected directly to a gateway, its throughput is decided only by the per-client throughput in local communications.

4.2. Throughput in Local Communications. Separate time slots are first assigned to different mesh routers so that simultaneous transmissions can only be carried out in cells that have enough distance in between; that is, simultaneous transmissions can only exist in cells that are $(\sqrt{\mathrm{CRF}}-1)$ 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 7, here CRF = 4.

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

$$\mathrm{TH}_{W_2}(i)=\frac{c_2W_2}{\mathrm{CRF}\times N_c(j)},\quad i=1\cdots N_c. \tag{13}$$

With the above TDMA scheme, all the mesh clients associated with the same mesh router will have the same throughput in local communications, that is, $\mathrm{TH}_{W_2}(i_1)=\mathrm{TH}_{W_2}(i_2)$, if clients i_1 and i_2 are associated with the same mesh router.



▨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 7: A TDMA scheduling scheme in local communications with CRF = 4.

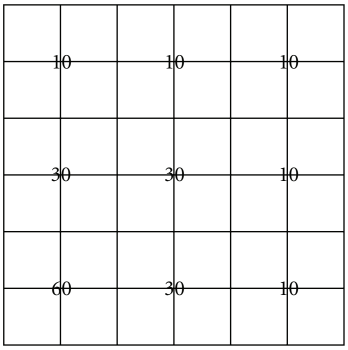


Figure 8: An example of uneven nodes' distribution.

4.3. Feasible Throughput in WMN. Combining (6)–(13), a feasible non-asymptotic throughput of the ith mesh client in the WMN can be obtained as follows:

$$\mathrm{TH}\left(i,N_g\right) = \min\left\{\left(\sum_{\substack{k=\text{all the associated gateways}\\ \text{with the mesh router } R^j}} \times \frac{G_{\text{eff}}(k)\times c_1W_1}{\sum_{\substack{l=\text{all associated routers}\\ \text{with the } k\text{th gateway}}}\left(N_C(l)\times N'_{\text{hop}}(l)\div N_g(l)\right)}\right) /N_g(j),\ \frac{c_2W_2}{\mathrm{CRF}\times N_c(j)}\right\}, \tag{14}$$

and here ith mesh client is assumed to be connected with the mesh router R^j. It is important to note that this non-asymptotic throughput estimation is more realistic than the asymptotic throughput that is estimated when the number of nodes approaches infinity.

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

$$\begin{aligned}\sum_{i=1}^{N_c}\mathrm{TH}\left(i,N_g\right) &\le \sum_{i=1}^{N_c}\mathrm{TH}_{W_2}(i)\\ &= \frac{c_2W_2}{\mathrm{CRF}}\times\sum_{j=1}^{N_r}u(j),\end{aligned} \tag{15}$$

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 per-client throughput:

$$\begin{aligned}\min_i \mathrm{TH}\left(i,N_g\right) &\le \min_i \mathrm{TH}_{W_2}(i)\\ &= \min_j \frac{c_2W_2}{\mathrm{CRF}\times N_c(j)}\\ &= \frac{c_2W_2}{\mathrm{CRF}\times \max_j N_c(j)}.\end{aligned} \tag{16}$$

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

It should be noted that the throughput computation method is applicable to any gateway placement algorithm; that is, as long as a gateway placement is given, the results derived in this section can be used to calculate the throughput of WMNs.

5. Numeric Results and Discussion

Using the framework of throughput computation derived in Section 4, throughput of this WMN is studied. In all the experiments we assume $N_c = 200$, $N_r = 36$, and $l = 1000$ m; that is, there are 200 mesh clients distributed in a square region of 1000 m × 1000 m; 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, SRD = 3, and Int D = 2.

Comparison study is conducted between the proposed algorithm (MTWP) and the other three gateway placement algorithms.

(i) *Random Placement* (RDP): N_g gateways choose their placement location randomly on N_r mesh routers.

(ii) *Busiest Router Placement* (BRP): N_g gateways choose their placement location on the N_r mesh routers with the highest traffic demand defined by $D(j)$, $j = 1\cdots N_r$.

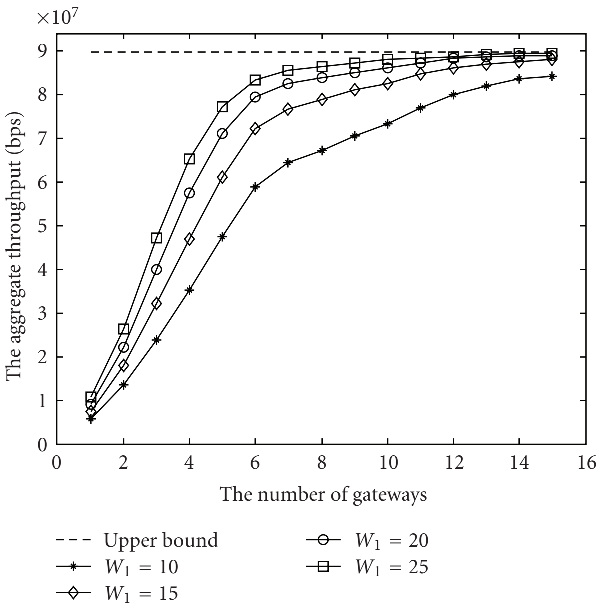


Figure 9: The aggregate throughput by changing the number of gateways with different channel capacity of mesh routers.

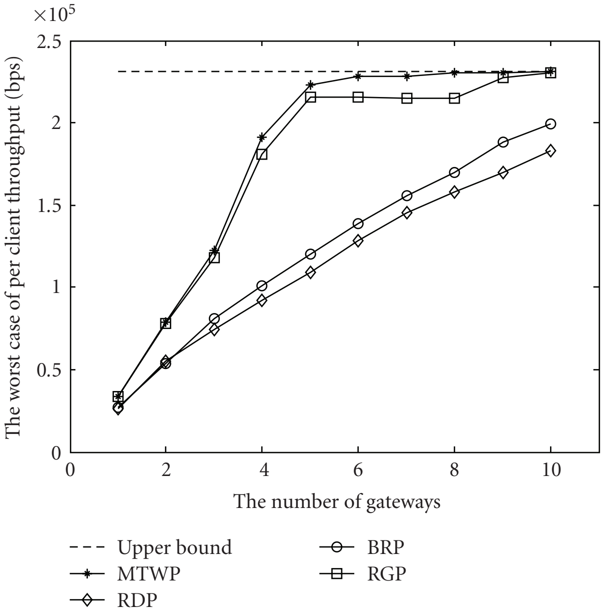


Figure 11: The comparison of the worst-case per-client throughput with uniformly distributed mesh clients.

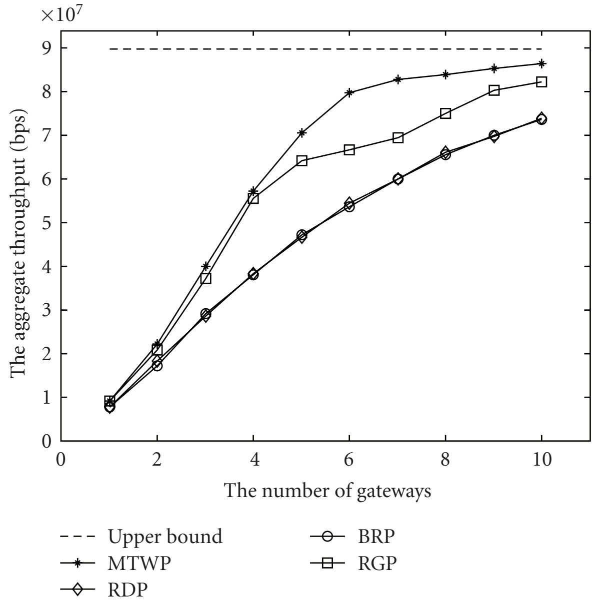


Figure 10: The comparison of the aggregate throughput with uniformly distributed mesh clients.

(iii) *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 $D(j)$, $j = 1 \cdots N_r$. Table 2 gives an example of RGP on a 6-by-6 regular grid.

Given a certain placement algorithm, a number of gateways will be placed on the top of the best-fit mesh routers. For each algorithm, per-client throughput is calculated based on (14). Then the aggregate throughput and the worst-case per-client throughput are obtained as described in Section 2.3. The upper bounds of the above two throughputs are calculated based on (15) and (16), respectively. Since mesh clients in all cases follow a random distribution, the results in all plots are obtained as an average over 200 iterations.

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 10 Mbps in downlink communications, that is, $c_2 W_2 = 10$ Mbps. The aggregate throughput of the WMN versus the number of gateways is shown in Figure 9, where gateways are placed by the proposed MTWP algorithm and the channel capacity of mesh routers varies from 10 Mbps to 25 Mbps with an increment of 5 Mbps. Our results confirm the fact that the number of gateways can be dramatically reduced by using more powerful mesh routers in the backbone; for example, 6 gateways with mesh router transmitting at 25 Mbps can achieve much better throughput performance than 15 gateways with mesh router transmitting at 10 Mbps.

In the second case, as shown in Figures 10 and 11, we compare throughput performance of four 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 10 Mbps and 20 Mbps, 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

Table 2: An example for 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), and (4,4)
2~4	Choose the N_g busiest routers from the location of (2,2), (2,5), (5,2), and (5,5)
5~7	Choose the first 4 gateways at the location of (2,2), (2,5), (5,2), and (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, for example, (1,1), (1,3), (1,5), (3,2), (3,4), (3,6), (5,1), (5,3), and (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

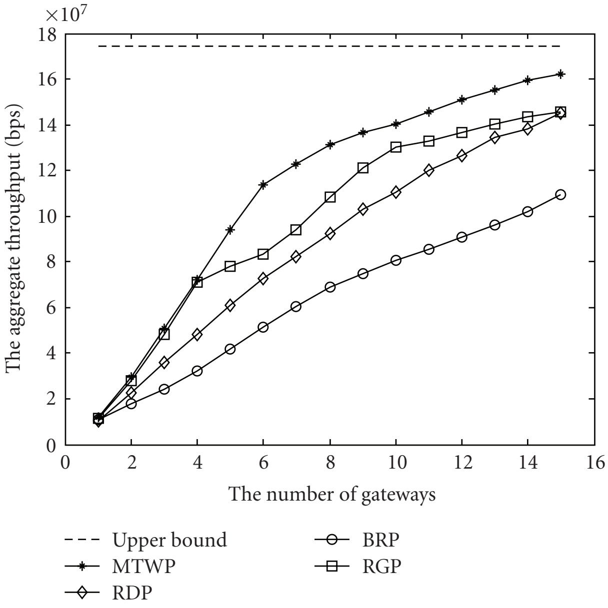


Figure 12: The comparison of the aggregate throughput with unevenly distributed mesh clients.

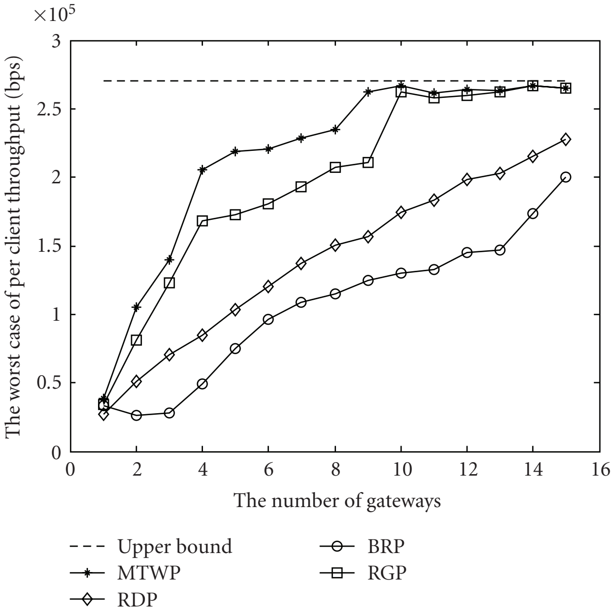


Figure 13: The comparison of the worst-case per-client throughput with unevenly distributed mesh clients.

can effectively reduce the average distance between a gateway and its associated mesh routers.

In the third case, as shown in Figures 12 and 13, we compare throughput performance of four gateway placement algorithms when mesh clients are distributed unevenly in the network, as depicted in Figure 8. Note that in each of the nine regions in Figure 8, nodes are still uniformly distributed; however, nodes density is very different among the nine regions. In this case, MTWP algorithm outperforms the other three algorithms in every single case. Here we double the channel capacity of mesh clients assuming that mesh clients and mesh routers can both transmit at 20 Mbps. Otherwise, improvements by gateway placement algorithms may not be observed since very low throughput of local communications becomes the major constraint for throughput performance of the whole WMN, which results from very high node density in some regions.

In both the second and third cases, as shown in Figures 10–13, the MTWP algorithm has the biggest improvement in throughput when the number of gateways is chosen from five to eight. An explanation is given as follows: with more than four gateways in a 6-by-6 grid backbone network, gateways start to interfere with each other. Comparing with the other three 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.

An important problem that WMN service providers face is the deployment cost involved in setting up the gateways. Thus, a performance metric to evaluate the cost of a gateway placement algorithm can be the aggregate throughput per gateway. Corresponding to Figure 10, the gateway placement costs are reflected in Figure 14. These results indicate that there exist an optimal number of gateways that achieve best tradeoff between the gateway cost and throughput. More importantly, it is illustrated that MTWP is the most cost-efficient scheme, since each gateway

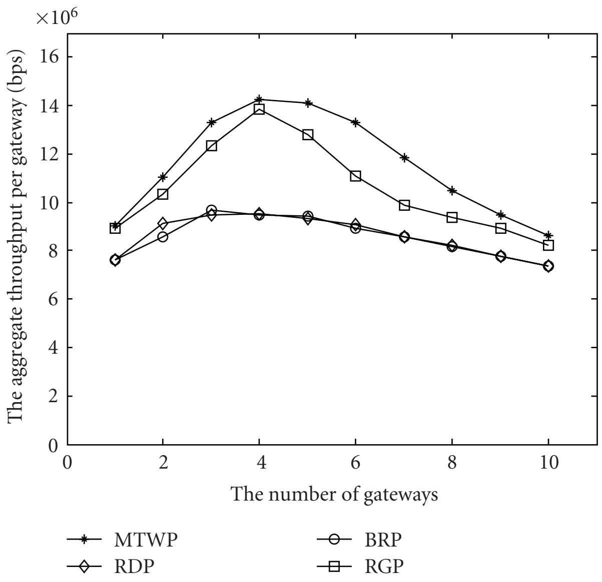


Figure 14: The comparison of the aggregate throughput per gateway with uniformly distributed mesh clients.

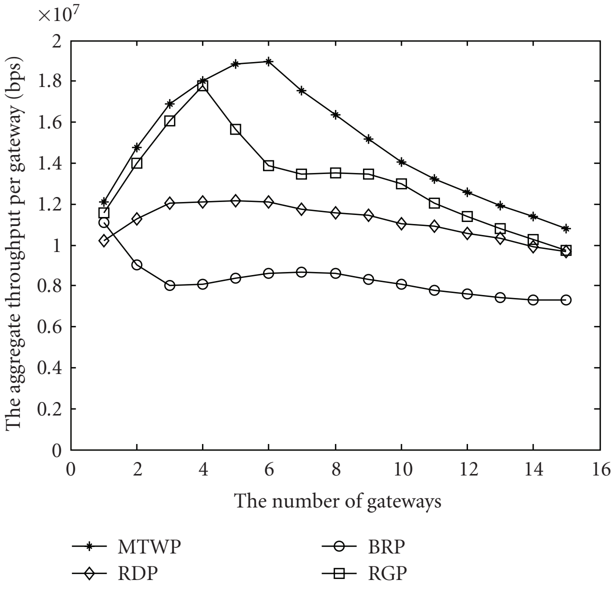


Figure 15: The comparison of the aggregate throughput per gateway with unevenly distributed mesh clients.

achieves the highest aggregate throughput. For unevenly-distributed mesh clients, results of throughput per gateway versus the number of gateways are shown in Figure 15. Again the MTWP algorithm is the most cost-effective.

6. Conclusion

The problem of gateway placement in WMNs for enhancing throughput was investigated in this paper. A gateway placement algorithm was firstly proposed based on multi-hop traffic weight. A non-asymptotic analytical model was also derived to determine the achieved throughput by a gateway placement algorithm. Based on such a model, the performance of the proposed gateway placement algorithm was evaluated. Numerical results illustrated the proposed algorithm achieved much better performance than other schemes. It was also proved to be a cost-effective solution.

It should be noted that the MTWP algorithm proposed in this paper did not consider the cross-optimization between gateway placement and throughput of WMNs. Thus, the throughput achieved by MTWP is not necessarily optimal and can be lower than the maximum throughput. Optimizing gateway placement together with throughput maximization is our next research goal.

References

[1] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: a survey,” *Computer Networks*, vol. 47, no. 4, pp. 445–487, 2005.

[2] S. Jamin, C. Jin, A. R. Kurc, D. Raz, and Y. Shavitt, “Constrained mirror placement on the Internet,” in *Proceedings of the Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM ’01)*, vol. 1, pp. 31–40, 2001.

[3] B. Li, M. J. Golin, G. F. Italiano, X. Deng, and K. Sohraby, “On the optimal placement of web proxies in the Internet,” in *Proceedings of the IEEE Conference on Computer Communications (INFOCOM ’99)*, vol. 3, pp. 1282–1290, 1999.

[4] L. Qiu, V. N. Padmanabhan, and G. M. Voelker, “On the placement of Web server replicas,” in *Proceedings of the Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM ’01)*, vol. 3, pp. 1587–1596, 2001.

[5] S. V. Hanly, “Algorithm for combined cell-site selection and power control to maximize cellular spread spectrum capacity,” *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 7, pp. 1332–1340, 1995.

[6] R. Mathar and T. Niessen, “Optimum positioning of base stations for cellular radio networks,” *Wireless Networks*, vol. 6, no. 6, pp. 421–428, 2000.

[7] K. Tutschku, “Demand-based radio network planning of cellular mobile communication systems,” in *Proceedings of IEEE Conference on Computer Communications (INFOCOM ’98)*, vol. 3, pp. 1054–1061, 1998.

[8] Y. Bejerano, “Efficient integration of multi-hop wireless and wired networks with QoS constraints,” in *Proceedings of the 8th Annual International Conference on Mobile Computing and Networking (MOBICOM ’02)*, September 2002.

[9] A. Srinivas, G. Zussman, and E. Modiano, “Mobile backbone networks—construction and maintenance,” in *Proceedings of the International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc ’06)*, pp. 166–177, 2006.

[10] A. So and B. Liang, “Minimum cost configuration of relay and channel infrastructure in heterogeneous wireless mesh networks,” in *Proceedings of the International IFIP-TC6 Networking Conference*, pp. 275–286, 2007.

[11] J. Wang, B. Xie, K. Cai, and D. P. Agrawal, “Efficient mesh router placement in wireless mesh networks,” in *Proceedings of IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS ’07)*, 2007.

[12] B. He, B. Xie, and D. P. Agrawal, “Optimizing the internet gateway deployment in a wireless mesh network,” in *Proceedings*

of IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS '07), 2007.

[13] F. Li, Y. Wang, and X.-Y. Li, "Gateway placement for throughput optimization in wireless mesh networks," in *Proceedings of IEEE International Conference on Communications (ICC '07)*, pp. 4955–4960, 2007.

[14] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory* , vol. 46, no. 2, pp. 388–404, 2000.

[15] P. Gupta and P. R. Kumar, "Internets in the sky: the capacity of three dimensional wireless networks," *Communications in Information and Systems*, vol. 1, no. 1, pp. 33–49, 2001.

[16] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad-hoc wireless networks," in *Proceedings of the Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '01)*, vol. 3, pp. 1360–1369, 2001.

[17] B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks," in *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '03)*, vol. 2, pp. 1543–1552, 2003.

[18] U. C. Kozat and L. Tassiulas, "Throughput capacity of random ad hoc networks with infrastructure support," in *Proceedings of the Annual International Conference on Mobile Computing and Networking (MOBICOM '03)*, pp. 55–65, 2003.

[19] A. Zemlianov and G. De Veciana, "Capacity of ad hoc wireless networks with infrastructure support," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 3, pp. 657–667, 2005.

[20] P. Zhou, X. Wang, and R. Rao, "Asymptotic capacity of infrastructure wireless mesh networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 8, pp. 1011–1024, 2008.

[21] J. Robinson and E. W. Knightly, "A performance study of deployment factors in wireless mesh networks," in *Proceedings of IEEE International Conference on Computer Communications (INFOCOM '07)*, pp. 2054–2062, May 2007.