Gateway Placement for Throughput Optimization in Wireless Mesh Networks

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***Abstract*— In this paper, we address the problem of gateway placement for throughput optimization in multi-hop wireless mesh networks. Assume that each mesh node in the mesh network has a traffic demand. Given the number of gateways need to be deployed (denoted by k) and the interference model in the network, we study where to place exactly k gateways in the mesh network such that the total throughput is maximized while it also ensures a certain fairness among all mesh nodes. We propose a novel grid-based gateway deployment method using a cross-layer throughput optimization. Our proposed method can also be extended to work with multi-channel and multi-radio mesh networks. Simulation result demonstrates that our method can effectively exploit the resources available and perform much better than random and fixed deployment methods.**

I. Introduction

Wireless mesh network (WMN) [1] draws lots of attention in recent years due to its various potential applications, such as broadband home networking, community and neighborhood networks, and enterprise networking. It has been used as the last mile solution for extending the Internet connectivity for mobile nodes. Many US cities (*e.g.*, Medford, Oregon; Chaska, Minnesota; and Gilbert, Arizona) have already deployed mesh networks. AWA, the Spanish operator of Wireless LAN networks, will roll out commercial WLAN and mesh networks for voice and data services. Several companies such as MeshDynamics have recently announced the availability of multi-hop multi-radio mesh network technology. These networks behave almost like wired networks since they have infrequent topology changes, limited node failures, *etc.*. For wireless mesh networks, the aggregate traffic load of each routing node changes infrequently also.

Wireless mesh networks consist of two types of nodes: mesh routers and mesh clients. Mesh routers form an infrastructure (called mesh backbone) for mesh clients that connect to them. The mesh backbone can be built using various types of radio technologies. The mesh routers form a mesh of self-configuring, self-healing links among themselves. Compared with a conventional wireless routers, mesh routers can achieve the same coverage with much lower transmission power through multi-hop communication. To connect the mesh network to the Internet, gateway devices are needed. Usually, in mesh networks some mesh routers have the gateway functionality which can provide the connectivity to the Internet. The common network infrastructure for mesh networks is illustrated in Figure 1, where dash and solid lines indicate wireless and wired links. We do not include the mesh clients in the figure, since this paper focuses on the design of the mesh backbone only. Hereafter, we will call the mesh routers without gateway functionality *mesh nodes* or just mesh routers, and call the mesh routers with gateway functionality *gateway nodes* to distinguish them from mesh nodes.

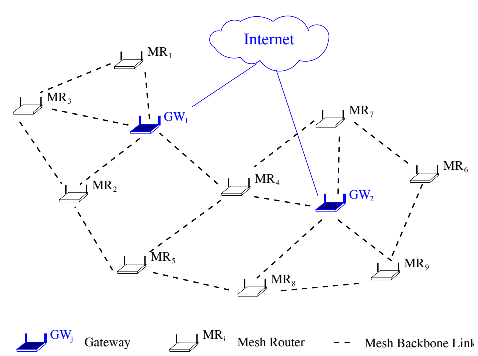


Fig. 1. Network infrastructure of wireless mesh network.

In this paper, we study how to design the mesh backbone to optimize the network throughput under the interference. More specifically, given the mesh backbone and the number of gateway devices, we investigate where to place the gateway devices in order to achieve optimal throughput. The application scenario of this gateway deployment problem for a community network is as follows. The mesh routers are placed on the roof of houses in a neighborhood, which serve as access points for users inside the homes and along the roads. All these mesh routers are fixed and form the mesh network. The mesh service provider needs to decide where to put the gateway devices to connect the mesh network to the Internet. Since different gateway deployment causes different mesh backbone topology and affects the network throughput, it is important to find optimal gateway deployment to maximize the throughput.

Optimizing the throughput has been studied in wireless networks. Gupta and Kumar [2] studied the asymptotic capacity of a multi-hop wireless networks. [3] and [4] further studied the capacity of wireless networks under different models. Kyasanur and Vaidya [5] investigated the capacity region on random multi-hop multi-radio multi-channel wireless networks. On the other aspect, several papers [6], [7] recently studied how to satisfy a certain traffic demand vector from all wireless nodes by a joint routing, link scheduling, and channel assignment under certain wireless interference models. Alicherry *et al.* [6] presented a linear programming based method to jointly perform multi-path routing, link scheduling, and *static* channel assignment for throughput optimization. Li *et al.* [8] also studied the throughput optimization via joint routing, link scheduling, and dynamic channel assignment for multi-radio multi-channel wireless networks. All these study either focused on the capacity of pure multi-hop mesh networks without gateways or assumed that the positions of mesh nodes and gateway nodes are fixed and given. In this paper, we consider the deployment of gateway nodes which affects the network throughput and capacity.

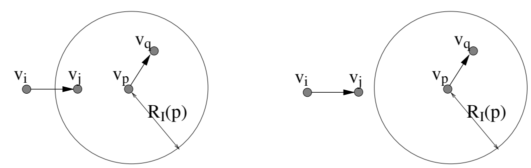
Deployment schemes of access points in WLAN has been studied [9]–[13] as well. However, most of the work focused on the guarantee of the coverage or how to provide better coverage using minimum number of access points. For example, Kouhbor *et al.* [13] studied how to find the optimal number of access points and their locations for WLAN in an environment that includes obstacles. Notice that WLAN is different with WMN since WLAN only supports single-hop wireless communication while WMN is a multi-hop network. For multi-hop networks or hybrid networks, until recently there is only a few study on deployment of relay nodes or access points. Pabst *et al.* [14] showed that deployment of fixed relay nodes can enhance capacity in hybrid cellular networks. Fong *et al.* [15] also studied some fixed broadband wireless access deployment schemes to increase the network capacity. However, to the best of our knowledge, there is no previous study on how to deployment gateways in wireless mesh networks to maximize the throughput.

The rest of the paper is organized as follows. In Section II, we present our network model and interference model. We then mathematically formulate the throughput optimization problem for a fixed mesh network in Section III. An efficient gateway deployment scheme for throughput optimization is presented in Section IV. We discuss possible extensions of our proposed scheme in Section V. Our simulation results are presented in Section VI. Section VII concludes our paper.

II. Models and Assumptions

Network Model: A mesh network is modeled by a *directed* graph $G = (V, E)$, where $V = \{v_1, \dots, v_n\}$ is the set of n nodes and E is the set of possible *directed* communication links. Let $\mathbf{E}^-(u)$ ($\mathbf{E}^+(u)$) denote the set of directed links that end (start) at node u. Every node v_i has a transmission range $R_T(i)$: $\|v_i - v_j\| \le R_T(i)$ is *not* the sufficient condition for $(v_i, v_j) \in E$. Some links do not belong to G because of either the physical barriers or the selection of routing protocols. We always use $\mathbf{L}_{i,j}$ to denote the directed link (v_i, v_j) hereafter. For each link $e = (u, v)$, the maximum rate at which a mesh router u can communicate with the mesh router v in one-hop communication supported by link e is denoted by $\mathbf{c}(e)$.

Among the set V of all wireless nodes, some of them are gateways which have gateway functionality and provide the connectivity to the Internet. For simplicity, let $\mathcal{S} = \{\mathbf{s}_1, \mathbf{s}_2, \cdots, \mathbf{s}_k\}$ be the set of k gateway nodes, where $\mathbf{s}_i$ is actually node v_{n+i-k}, for $1 \le i \le k$. All other wireless nodes v_i (for $1 \le i \le n-k$) $\in \overline{\mathcal{S}} = V - S$ are *ordinary* mesh nodes. Each ordinary mesh node u will aggregate the traffic from all its users and then route them to the Internet through some gateway nodes. We assume that the capacity between any gateway node to the Internet is sufficiently large. We use $\ell_O(u)$ ($\ell_I(u)$) to denote the total aggregated outgoing (incoming) traffic for its users by mesh node u. We will mainly concentrate on one of the traffics in this paper, say incoming traffics. For notation simplicity, we use $\ell(u)$ to denote such load for node u. Notice that the traffic $\ell(u)$ is not requested to be routed through a specific gateway node, neither requested to be using a single routing path. Our results can be easily extended to deal with both incoming and outgoing traffic by defining routing flows for both traffics separately.



(a) v_j interfered by v_p (b) v_j not interfered by v_p

Fig. 2. Illustration of fPrIM interference model.

Interference Model: Each node v_i also has an interference range $R_I(i)$ such that node v_j is interfered by the signal from v_i whenever $\|v_i - v_j\| \le R_I(i)$ and v_j is not the intended receiver. The interference range $R_I(i)$ is not necessarily same as the transmission range $R_T(i)$. Typically, $R_T(i) < R_I(i) \le c \cdot R_T(i)$ for some constant $c > 1$. The *Interference-Transmission Ratio* for node v_i is defined by $\gamma_i = \frac{R_I(i)}{R_T(i)}$. In practice, $2 \le \gamma_i \le 4$. For all wireless nodes, let $\gamma = \max_{v_i \in V} \frac{R_I(i)}{R_T(i)}$. To schedule two links at the same time slot, we must ensure that the schedule will avoid the link interference. Different types of link interference have been studied in the literature, such as *Protocol Interferences Model* (PrIM) [2], *Fixed Protocol Interferences Model* (fPrIM) [8], [16], *RTS/CTS Model* (RTS-CTS) [6], and *Transmitter Interference Model* (TxIM) [17]. In this paper we adopt the fPrIM by assuming that any node v_j will be interfered by the signal from v_p if $\|v_p - v_j\| \le R_I(p)$ and node v_p is sending signal to some node other than v_j. See Figure 2(a). In other words, the transmission from v_i to v_j is viewed successful if $\|v_p - v_j\| > R_I(p)$ for every node v_p transmitting in the same time slot, as shown in Figure 2(b). Actually, our gateway deployment method can work for any kind of interference model as we will discuss in Section V. Given a network $G = (V, E)$, we use the *conflict graph* (*e.g.*, [18]) F_G to represent the interference in G. Each vertex (denoted by $\mathbf{L}_{i,j}$) of F_G corresponds to a directed link (v_i, v_j) in the communication graph G. There is a *directed edge* from vertex $\mathbf{L}_{i,j}$ to vertex $\mathbf{L}_{p,q}$ in F_G if and only if the transmission of $\mathbf{L}_{i,j}$ interferences the reception of the receiving node of link $\mathbf{L}_{p,q}$.

III. Throughput Optimization in Mesh Networks

In this section, we study what is the best throughput achievable by a given multi-hop mesh networks using best possible routing and link scheduling. Here, we assume that the routing between a given mesh router and some gateway nodes can use multiple paths, i.e, the aggregated traffics can be infinitely divisible. We also assume the time is slotted and synchronized. Every mesh router u has a traffic demand $\ell(u)$ that needs to be routed to the Internet via some gateway nodes. We want to maximize the total routed traffic to the Internet while certain minimum traffic from each mesh router should be satisfied. Our approach is to give each link $\mathbf{L} \in G$ an interference-aware transmission schedule $\mathcal{S}(\mathbf{L})$ which assign the time slot for transmission to maximize the overall network throughout. A link scheduling is to assign each link a set of time slots $\subset [1, T]$ in which it can transmit, where T is the scheduling period. A link scheduling is *interference-aware* (or called *valid*) if a scheduled transmission on a link $x \rightarrow y$ will not result in a collision at either node x or node y (or any other node) due to the simultaneous transmission of other links. Let $X_{e,t} \in \{0, 1\}$ be the indicator variable which is 1 if and only if e will transmit at time-slot t. We focus on periodic schedules here. A schedule is periodic with period T if, for every link e and time slot t, $X_{e,t} = X_{e,t+i\cdot T}$ for any integer $i \geq 0$. For a link e, let $\mathbf{I}(e)$ denote the set of links e' that will cause interference if e and e' are scheduled at the same time slot. A schedule $\mathcal{S}$ is *interference-free* if $X_{e,t} + X_{e',t} \leq 1, \forall e' \in \mathbf{I}(e)$.

We now provide a mixed Integer Programming formulation of the throughput optimization. For cross-layer optimization, the flow supported by mesh networks not only needs to satisfy the capacity constraint, but also needs to be schedulable by all links without interference.

We first formulate the routing problem to maximize the throughput of the achieved flow under certain fairness constraints. Let $\alpha(e) \in [0, 1]$ denote the fraction of the time slots in one scheduling-period that link e is actively transmitting. Obviously, $\alpha(e) \cdot \mathbf{c}(e)$ is the corresponding achieved flow. Given a routing (and corresponding link scheduling), the achieved fairness λ is defined as the minimum ratio of *achieved flow* over the *demanded load* over all wireless mesh routers. Assume that we have a minimum fairness constraints λ_0. Clearly, the achieved flow at a router u is difference between the flow goes out of node u and the flow comes to node u, *i.e.*, $\sum_{e\in\mathbf{E}^+(u)} f(e) - \sum_{e\in\mathbf{E}^-(u)} f(e)$. Here $f(e)$ is the total scheduled traffics over link e. The maximum throughput routing is equivalent to solve the following linear programming (**LP-Flow-Throughput-1**) for $\alpha(e, \mathbf{f})$ such that

LP-Flow-Throughput-1: $\max \sum_{i=1}^{k} f(\mathbf{s}_i)$

$$\begin{cases} \sum_{e\in\mathbf{E}^+(u)} f(e) - \sum_{e\in\mathbf{E}^-(u)} f(e) & = f(u) & \forall u \in \overline{\mathcal{S}} \\ f(u) & \geq \lambda_0 \ell(u) & \forall u \in \overline{\mathcal{S}} \\ \sum_{e\in\mathbf{E}^-(\mathbf{s}_i)} f(e) - \sum_{e\in\mathbf{E}^+(\mathbf{s}_i)} f(e) & = f(\mathbf{s}_i) & \forall \mathbf{s}_i \in \mathcal{S} \\ \alpha(e)\cdot\mathbf{c}(e) & = f(e) & \forall e \\ \alpha(e) & \geq 0 & \forall e \\ \alpha(e) & \leq 1 & \forall e \\ exists \text{ interfence-free schedule for} & \alpha(e) & \end{cases}$$

Our objective of periodic TDMA link scheduling is to give each link $\mathbf{L} \in G$ a transmission schedule $\mathcal{S}(\mathbf{L})$, which is the list of time-slot that a link can send packets such that the schedule is interference-free. We then mathematically formulate a necessary, sufficient condition for schedulable flow $f(e) = \alpha(e) \cdot \mathbf{c}(e)$: a flow f (equivalently, whether a given vector $\alpha(e)$ for all e is schedulable) is schedulable iff we can find integer solution $X_{e,t}$ satisfying the following conditions.

Necessary and Sufficient Condition for Schedulable Flow:

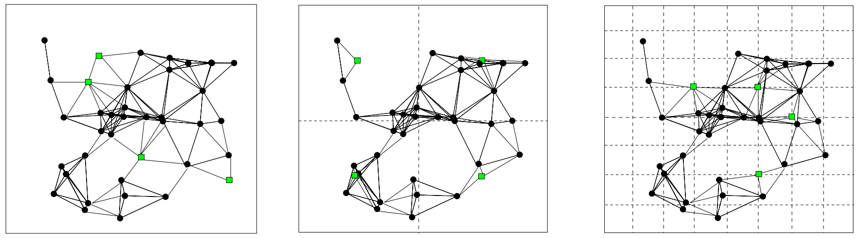
$$\begin{cases} X_{e,t} + X_{e',t} & \leq & 1 & \forall e' \in \mathbf{I}(e), \forall e, \forall t \\ \frac{\sum_{1\leq t\leq T} X_{e,t}}{T} & = & \alpha(e) & \forall e \\ X_{e,t} & \in & \{0, 1\} & \forall e, \forall t \end{cases}$$

The first condition says that a schedule should be interference-free. The second condition says that the schedule should achieve the required flow $\alpha(e)$. It is widely known that it is NP-hard to decide whether a feasible scheduling $X_{e,t}$ exists when given the flow $f(e)$ (or equivalently, $\alpha(e)$) for wireless networks with interference constraints. For some interference models several papers gave relaxed necessary conditions and relaxed sufficient conditions for schedulable flows that can be decided in polynomial time. For example, [8] proved a necessary and a sufficient condition for schedulable flows under different interference model. Consider the active fraction $\alpha(e) \in [0, 1]$ of each link. A sufficient condition that this α is schedulable is, for each e, $\alpha(e) + \sum_{e'\in\mathbf{I}_{\mathcal{M}}(e)} \alpha(e') \leq 1$. A necessary condition that this α is schedulable is, for each e, $\alpha(e) + \sum_{e'\in\mathbf{I}_{\mathcal{M}}(e)} \alpha(e') \leq C_{\mathcal{M}}$. Here $\mathbf{I}_{\mathcal{M}}(e) \subseteq \mathbf{I}(e)$ is defined based on the specific interference model $\mathcal{M}$ for the purpose of link scheduling; $C_{\mathcal{M}}$ is a constant depending on the specific interference model and γ. For the fPrIM, $C_{\mathcal{M}} = \lceil \frac{2\pi}{\arcsin\frac{\gamma-1}{2\gamma}} \rceil$, *e.g.*, $C_{\mathcal{M}} = 25$ when $\gamma = 2$ [8]. Then we can relax the original mixed Integer Programming to a linear programming by getting rid of the scheduling variables X. Based on previous study, we generally require that, given a constant integer $C \in [1, C_{\mathcal{M}}]$, we need to solve the following Linear Programming (**LP-Flow-Throughput-2**) for $\alpha(e)$ such that

LP-Flow-Throughput-2: $\max \sum_{i=1}^{k} f(\mathbf{s}_i)$

$$\begin{cases} \sum_{e\in\mathbf{E}^+(u)} f(e) - \sum_{e\in\mathbf{E}^-(u)} f(e) & = f(u) & \forall u \in \overline{\mathcal{S}} \\ f(u) & \geq \lambda_0 \ell(u) & \forall u \in \overline{\mathcal{S}} \\ \sum_{e\in\mathbf{E}^-(\mathbf{s}_i)} f(e) - \sum_{e\in\mathbf{E}^+(\mathbf{s}_i)} f(e) & = f(\mathbf{s}_i) & \forall \mathbf{s}_i \in \mathcal{S} \\ \alpha(e)\cdot\mathbf{c}(e) & = f(e) & \forall e \\ \alpha(e) & \geq 0 & \forall e \\ \alpha(e) & \leq 1 & \forall e \\ \alpha(e) + \sum_{e'\in\mathbf{I}_{\mathcal{M}}(e)} \alpha(e') & \leq C & \forall e \end{cases}$$

In [16], Wang *et al.* studied the interference aware TDMA link scheduling for networks of single channel. We can apply their greed method to design efficient link scheduling that can achieve $\alpha(e)$ found from the solution of the LP. Assume that we already have the values $\alpha(e)$ for every links e and T is the number of time slots per scheduling period. Then we need to schedule $T \cdot \alpha(e)$ time-slots for a link e. For simplicity, we assume that the choice of T results that $T \cdot \alpha(e)$ is integer



(a) Random Deployment (b) Fixed Deployment (c) Grid-based Deployment

Fig. 3. Three gateway deployment methods: 4 gateways (grey squre) are deployed in a mesh network with 33 mesh nodes (black dot).

for every e. Notice that when we schedule each link, we need to ensure that the scheduling is interference-free. Algorithm 1 illustrates our scheduling method. The basic idea of our scheduling is first sorting the links based on some specific order and then process the requirement $\alpha(e)$ for each link in a greedy manner. When process the i^{th} link e_i, we assign link e_i the *earliest* (not need to be consecutive) $N(e_i) = T \cdot \alpha(e_i)$ time slots that will not cause any interference to already scheduled links.

Algorithm 1 Greedy Link Scheduling

Input: A communication graph $G = (V, E)$ of m links and $\alpha(e)$ for all links.
Output: An interference-free link scheduling.

Sort the links in the communication graph G according the interference model. For fPrIM model, we consider the conflict graph F_G. We choose the vertex, which is the link in the original graph, with the largest value $d_{i,j}^{in} - d_{i,j}^{out}$ in the residue conflict graph; remove the vertex and its incident edges. Here, $d_{i,j}^{in}$ and $d_{i,j}^{out}$ are the *in-degree* and *out-degree* of vertex $\mathbf{L}_{i,j}$ in the conflict graph under fPrIM model. Repeat this process until there is no vertex in the conflict graph. Then the links (in the original graph) are sorted by their reverse removal order. Let $(e_1, e_2, \cdots, e_m)$ be the sorted list of links.
for $i = 1$ to m **do**
  $N(e_i) = T \cdot \alpha(e_i)$ be the number of time slots that link e_i will be active.
  Assume $e_i = (u, v)$. Set $allocated \leftarrow 0$; $t \leftarrow 1$;
  while $allocated < N(e_i)$ **do**
    if $X_{e',t} = 0$ for every conflicting link $e' \in \mathbf{I}_{\mathcal{M}}(e_i)$, $\sum_{e':e' \ni u} X_{e',t} < 1$, $\sum_{e':e' \ni v} X_{e',t} < 1$ **then**
      Set $X_{e_i,t} \leftarrow 1$; Set $allocated \leftarrow allocated + 1$;
    Set $t \leftarrow t + 1$.

In [8], the authors proved that Algorithm 1 produces a feasible interference-free link scheduling when $\alpha(e)$ is a feasible solution of LP using $C = 1$.

IV. Gateways Placement Schemes

We provide a method (Algorithm 1 together with the linear programming formulation **LP-Flow-Throughput-2**) in Section III to achieve a interference-free link scheduling which maximizes the network throughput. In other words, this method can be used to evaluate a fixed mesh networks with certain gateways in term of throughput optimization. In this section, we propose a grid-based gateway placement scheme which uses the linear programming **LP-Flow-Throughput-2** as a evaluation tool. The problem we want to study is as follows:

The Problem: Given a mesh network with $n-k$ fixed mesh nodes and interference model, our gateway placement needs to select positions for k gateways in order to maximize the throughput. It is clear that we can not try all possible positions since the possible combination is infinite.

Random Deployment: The easiest and simplest method is random deployment where we randomly select k positions for gateways. For example, Figure 3(a) shows 4 gateways are deployed randomly in a mesh network. However, the random deployment maybe not good at the throughput or even can not guarantee the connectivity of the mesh network.

Fixed Deployment: The second method is to deployment the gateways in fixed positions which are the centers of evenly distributed cells. As shown in Figure 3(b), to place 4 gateways, we divide the whole area into 4 cells and put the gateways in the centers of these cells. This fixed deployment scheme should be able to work well with well-spread and evenly-distributed mesh networks. However, if the network is not so even, for example, putting a gateway at the center of the left-upper cell in Figure 3(b) does not help a lot for the throughput since the gateway can only connect 2 mesh nodes and one of them is an end-point. In the real-life applications, the mesh network usually is not evenly-distributed. For example, houses are arbitrarily distributed in a neighborhood due to different designs and various landscapes (e.g, a lake or a hill).

Grid Based Deployment: To explore more choices of gateway layouts but at the same time to keep the scalability of the method, we propose a new grid based deployment scheme. The idea is simple. The whole deployment area is divided into an $a \times b$ grid. As shown in Figure 3(c), we only place the gateways in the cross points on this grid. We will try all possible combinations of the k-gateway placement, and evaluate each of them using the method in previous section (computing the maximum throughput can be achieved by this combination). Finally, we select the placement which has the largest maximum throughput. For an $a \times b$ grid, the number of total combinations is $C_{a \times b}^{k}$ which is the combination of selecting k elements from $a \times b$ elements. Even though this number could be large, it is still reasonable to try all of them since the deployment scheme will only run once before the real gateway installation and the positions of all mesh routers are fixed. In addition, the overhead cost depends on the size of the grid. It is an adjustable parameter which can be easily controlled for the tradeoff between computation overhead and throughput performance. If both a and b goes to infinite, our grid-based method can potentially explore all possible deployment layouts.

We will test all these three methods by conducing simulations with random networks in Section VI.

V. Discussions

So far, we only consider the network with a single channel and using fPrIM model. However, our gateway placement method based on throughput optimization can be extended for various networks with different models.

Various Interference Models: Our maximum throughput method can be extended to deal with different interference models, such as PrIM [2], RTS-CTS [6], and TxIM [17]. The differences of these models with the fPrIM are that they have different definitions of link interference. The only changes needed in our method are (1) the sorting method in Step 1 of Algorithm 1; and (2) the constant $C_{\mathcal{M}}$ with respect to all interference models $\mathcal{M}$. In [8], the authors showed how to do the sorting under different interference models for link scheduling and provided the values of $C_{\mathcal{M}}$ for those models.

Multi-channel and Multi-radio Networks: A number of schemes [19]–[22] have been proposed recently to exploit multiple channels and multiple radios for performance improvement in wireless mesh networks. Using multiple channels and multiple radios can alleviate but not eliminate the interference. For multi-channel and multi-radio mesh networks, we can first convert the network model (the graph model) G to a single-radio and multi-channel graph model G' by splitting a node with p radio interface to p pseudo nodes, then refine our linear programming for throughput optimization by define the fraction of flow for each pair of e and $\mathbf{f}$ instead of just e. The link scheduling in multi-channel and multi-radio mesh networks also needs to satisfy the channel and radio constraints no matter whether dynamic channel assignment or fixed channel assignment is used. The greedy link scheduling (Algorithm 1) can also be extended to schedule the links and channels. The basic idea is as follows. When processing the ith link $e_i \in G'$, we process the channels in order and assign link e_i the earliest $N(e_i, \mathbf{f}) = T \cdot \alpha(e_i, \mathbf{f})$ time slots using channel $\mathbf{f}$ that will not cause any interference to already scheduled links, and satisfy the radio and channel-availability constraints.

VI. Simulations

In this section, we evaluate the maximal flow of different gateway deployment schemes in random wireless mesh networks. As we have discussed in Section III, the maximal flow is solved by a linear programming. The wireless mesh network in our simulation is randomly generated, i.e., the positions of n mesh nodes are randomly chosen in certain area. For each generated mesh network, the deployment method will decide how to place k gateways to connect the mesh routers to Internet. We use $802.11a$ for the link channel capacity in the wireless mesh network, which is the same as [6]. The link channel capacity thus only depends on the distance between the two nodes at the end of each link. We set the link channel capacity as $54Mbps$ when the distance of the two end nodes is within 30 meters, $48Mbps$ when the distance is within 32 meters, $36Mbps$ when the distance is within 37 meters, $24Mbps$ when the distance is within 45 meters, $18Mbps$ when the distance is within 60 meters, $12Mbps$ when the distance is within 69 meters, $9Mbps$ when the distance is within 77 meters, and $6Mbps$ when the distance is within 90 meters. Otherwise, if the distance of the two end nodes of the link is beyond 90 meters, we will set the link channel capacity as 0. Each node has 180 meters interference range. The wireless mesh network is generated with 60-100 mesh routers and 4-8 gateways. The mesh routers are randomly dispersed in a square area of 500×500 square meters. Each mesh router transfers $20Mbps$ data to the Internet. The input value of λ_0 and C in the LP to solve the maximal throughput is set as 0.2 and 20.

We evaluate three gateway deployment schemes described in Section IV. The fixed deployment scheme first divides the square area into k equal cells as shown in Figure 4(a)-(c), and then put the k gateways in the centers of these cells. Our grid-based deployment scheme will use various grids defined in Figure 4(d)-(e) to define the candidate positions of gateways, and then try all the combinations of positions using the LP to evaluate their throughput, and select the combination with highest throughput.

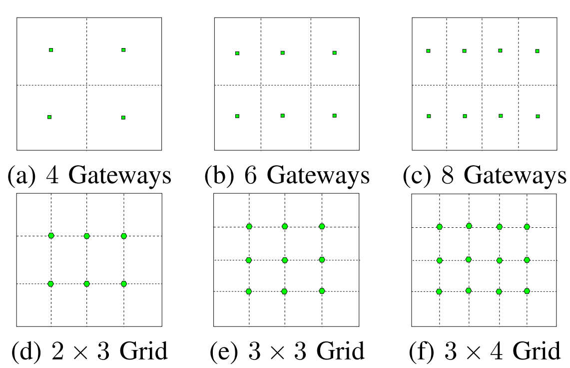


Fig. 4. The layouts of gateways in fixed deployment scheme (a-c) and the grids used in our deployment scheme (d-f).

We vary the numbers of mesh routers, mesh gateways and cells of the grid to test the performance of these three deployment schemes. Each data in Tables I, II and III is the average number computed over all 100 random networks.

Table I shows the results for networks with 60, 80 and 100 mesh routers and 6 gateways to be deployed. It is clear that our grid-based method can achieve better throughput than the random and fixed schemes. Notice that there are many cases that the random deployment method can not find feasible solutions in LP (due to the minimum fairness constraints) or even can not form a connected mesh network. We exclude those cases in the results present in Table I and II. In other words, all the data here are for the mesh network where the random deployment can find the feasible solution.

Table II shows the results when we want to deploy various number of gateways. The number of gateways is from 4 to 8 when the number of mesh routers are fixed at 60. It is clear that with more gateways the performance is better.

Table III shows the results when we increasing the size of the grid from 2×3 to 3×4 when the number of gateway is fixed at 6. Here, we do not request the network need to have feasible solution for the random deployment. Thus, the data in Table III are different with the data in Tables I and II, even though the number of gateways, nodes and grids are the same. It is clear that the larger size of grid can improves the throughput, but also increases the computation cost. Therefore, in practice, the administrator needs to find an appropriate grid to satisfy both performance and cost requirements. On the other hand, by having the ability to change the grid size, it gives the way for administrator to play with the tradeoff.

TABLE I
AVG THROUGHPUT (VARIOUS NETWORK SIZES)

Nodes	Gateways	Random	Fixed	3 × 4 Grid
60	6	551.3	677.6	831.2
80	6	686.1	845.5	959.9
100	6	783.2	947.5	1082.0

TABLE II
AVG THROUGHPUT (VARIOUS NUMBERS OF GATEWAYS)

Nodes	Gateways	Random	Fixed	3 × 4 Grid
60	4	393.4	442.6	648.7
60	6	551.3	677.6	831.2
60	8	721.1	854.4	952.3

TABLE III
AVG THROUGHPUT (VARIOUS GRID SIZES)

Nodes	Gateways	2 × 3 Grid	3 × 3 Grid	3 × 4 Grid
60	6	681.6	756.3	820.5
80	6	787.6	852.8	944.3
100	6	962.5	977.3	1083.8

VII. CONCLUSION

The positions of gateways in wireless mesh networks affect the total network throughput. In this paper, we studied how to place k gateways for a mesh network so that the total throughput achieved by interference-free scheduling is maximized. We proposed a novel grid-based gateway deployment method using a cross-layer throughput optimization. Our proposed method can be extended to work with multi-channel and multi-radio networks under various interference models. Our simulation results demonstrated that our method achieves better throughput than both random deployment and fixed deployment methods.

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