Abstract

In this paper, we consider the problem of topology control by joint power control and routing to maximize the network throughput in wireless mesh networks. First, we present two mathematical formulations of the joint power control and routing problem according to two different definitions of network throughput: the total throughput and the minimal per-node throughput. To reduce the computation cost, we next decompose this joint problem into two sub-problems: the power control sub-problem and the routing sub-problem. For the first sub-problem, we design two heuristic algorithms to assign transmission powers to mesh routers, such that the total interference or the maximum node interference in the network is minimized. For the routing sub-problem, we design two linear programming formulations to maximize the total throughput or the minimal per-node throughput. Simulation results reveal the following relationship: the topology with minimum total interference has higher total throughput, while the topology with minimum maximal node interference has higher minimal per-node throughput. This can serve as a guidance for network design to satisfy different throughput considerations.

1 Introduction

Wireless mesh networks (WMNs) [1] have attracted much attention due to their potential applications, such as last-mile broadband Internet access, neighborhood gaming, distributed file storage and real-time multimedia applications. Since a high volume of traffic is expected to be efficiently delivered in such networks, the network throughput is the main consideration in designing wireless mesh networks. In this paper, we consider the problem of topology control by joint power control and routing to maximize the network throughput. Given a wireless mesh network that consists of a number of mesh routers, supposing each router can adjust its transmission power and has a traffic demand, our task is to assign a transmission power to each router and decide how to route their traffic to the Internet through gateways, such that the total network throughput or the minimal per-node throughput is maximized. Gateways are the routers that are directly connected with the Internet.

The problem of power control has been studied extensively in wireless ad hoc networks [4, 8]. However, these algorithms are energy-oriented, which target to reduce the power consumption, and a tradeoff is made between the network throughput and the lifetime of energy-limited nodes. In addition, other characteristics of ad hoc networks also restrict their performance, such as node mobility and node failure. Due to the special characteristics of WMNs, they are not suitable to be applied in WMNs. First, mesh routers which form the network backbones are rarely mobile and have no power constraint. Second, there are very much limited node failures in WMNs. Therefore, the network topology does not change frequently. Finally, since each mesh router is responsible to aggregate traffic flows from a number of mobile clients, the aggregate traffic demand of each mesh router remains nearly the same over time [2]. Therefore, a new scheme that can make full use of the special characteristics of WMNs should be designed.

In this paper, we first present two mathematical formulations of the joint power control and routing problem according to two different definitions of network throughput: the total traffic finally routed to the Internet of all nodes (total throughput), and the minimal routed traffic of every node (minimal per-node throughput). To reduce the computation cost, we next decompose this joint problem into two sub-problems: the power control sub-problem at the physical layer and the routing sub-problem at the network layer. For the power control sub-problem, we design two heuristic algorithms to assign transmission powers to mesh routers, such that the total interference or the maximum node interference in the network is minimized. For the routing sub-problem, we design two linear programming formulations to maximize the total throughput or the minimal per-node throughput. Finally, we show how to solve the joint problem by four different combinations of the solutions designed.
for the sub-problems. By analyzing the simulation results, we find the following relationship: the topology with minimum total interference has higher total throughput, while the topology with minimum maximal node interference has higher minimal per-node throughput. This can serve as a guidance for network design to satisfy different throughput considerations.

The rest of the paper is organized as follows. We discuss the related work in Section 2 and describe our system architecture in Section 3. In Section 4, we present the mathematical formulations of the joint power control and routing problem. The sub-problems and their solutions are described in Section 5. Our approaches are evaluated through extensive simulations and the results are analyzed in Section 6. Finally, Section 7 concludes this paper.

2 Related Works

The problem of topology control by adjusting transmission power has been studied extensively in wireless ad hoc networks. One of the classical works [13] studied the optimal transmission power of nodes in multi-hop networks to maximize the expected progress of packets in the direction towards the receivers. This work assumes all nodes uses the same transmission power. Jia et al. proposed a QoS topology control mechanism for ad hoc networks in [7], which constructs a network topology that can meet end-users’ QoS requirements and has the minimal total transmission power. They also systematically studied the connectivity issue in ad hoc networks in [6] and proposed several approximation algorithms for computing k-connectivity topology that uses minimal transmission power. Tang et al. [15] study the problem of joint link scheduling and power control in a TDMA-based multi-hop WMNs with the objective of maximizing network throughput. A tradeoff is applied between network throughput and fairness in order to avoid severe bias on bandwidth allocation among links, which is similar to a part of our problem. Finally, different definitions of interference and several algorithms which target to construct network topologies such that maximum (or average) link (or node) interference of the topology is either minimized or approximately minimized are presented in [10].

An alternative way to control the network topology and improve the network throughput is to exploit multiple channels in WMNs. Some of the recent works studied joint channel assignment and routing [2, 12, 16], joint routing and link scheduling [9, 14] and joint channel assignment and MAC design [11]. A novel channel assignment protocol is also proposed in [17]. All these works require routers to be equipped with multiple radios, or one radio that can switch its channel very quickly.

Besides the techniques designed for physical or MAC layer, or cross-layer protocols, many works also studied the problem of traffic routing in network layer alone. The problem of fairness and end-to-end performance in multihop wireless networks is studied in [5]. They presented a formal reference model, based on which they developed a distributed fairness algorithm and studied the critical relationship between fairness and aggregate throughput. Yang et al. [18] formulated the problem of load balancing in WMNs and provided a theoretical solution. Then they proposed a new path weight function and a novel routing scheme to achieve interference-aware load balancing in WMNs. An on-demand routing protocol that exploits a new link weight metric is presented in [3]. However, their objective is to find a high-throughput path between a source and a destination, rather than the throughput of the whole network.

3 System Architecture

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

In this paper, we consider the backbone of a single radio and single channel wireless mesh network. The backbone consists of N heterogeneous mesh routers, M of which are gateways. Each mesh router is equipped with only one network interface (NIC) that can adjust its transmission power. The transmission power is measured as the valid distance for a receiver to decode the sender’s signal and the number of available transmission power levels for node u is K_u. All routers work on the same channel. We denote the aggregate traffic demand of node u by \lambda_u and the transmission capacity of its NIC by B_u. Note that different mesh routers may have different number of transmission power levels and different node transmission capacities. The traffic demand \lambda_u may be the sum of the upstream and downstream traffic loads. However, for ease of explanation, we assume that \lambda_u represents only the upstream traffic. We also assume \lambda_u exhibits only long term variability and such variations can be dealt with by re-adjusting transmission power assignments and re-routing traffic load. This assumption is reasonable since the aggregate traffic demand of each router and the network topology do not change frequently in WMNs.
4 Problem Formulation

Our task in this paper is to assign a transmission power to each router and decide how to route their traffic to the Internet through gateways, such that the network throughput is maximized. The network throughput is defined as either the total traffic that are finally routed to the Internet from all routers, or the minimal percentage of traffic demand of each router which is actually routed to the Internet.

The network backbone is modeled as a directed graph $G = (V, E)$, where $V = \{v_1, v_2, \ldots, v_n\}$ is the set of mesh routers and $E$ is the set of possible directed communication links. The joint power control and routing problem can be mathematically formulated as follows.

4.1 Topology Control Constraints

For each node $u \in V$, we denote its $K_u$ transmission power levels as $\{t_{u}^1, t_{u}^2, \ldots, t_{u}^{K_u}\}$. The following two indicator variables are defined:

$$x_u^i = \begin{cases} 1 & \text{if } u \text{ selects power level } t_{u}^i, 1 \leq i \leq K_u \\ 0 & \text{otherwise} \end{cases}$$

$$l_{uv} = \begin{cases} 1 & \text{if } d(u, v) \leq p_u, p_u \in \{t_{u}^1, t_{u}^2, \ldots, t_{u}^{K_u}\} \\ 0 & \text{otherwise} \end{cases}$$

Only after each node is assigned a transmission power, can we be able to construct the communication link set $E$ by using $l_{uv}$, which denotes whether there is a directed link from node $u$ to $v$. A directed link $(u, v) \in E$ exists if and only if $l_{uv} = 1$. In the definition above, $p_u$ is the transmission power finally assigned to node $u$ and $d(u, v)$ is the Euclidean distance between $u$ and $v$. Remember that in this paper, the transmission power is measured as the valid distance for a receiver to decode the sender’s signal. The value of $l_{uv}$ can be decided by the following inequality:

$$\min\{\sum_{i=1}^{K_u} t_{u}^i x_u^i - d(u, v) + \epsilon, \epsilon\} \leq l_{uv} d(u, v) \leq \sum_{i=1}^{K_u} t_{u}^i x_u^i$$  \hspace{1cm} (1)

where $\epsilon$ is arbitrarily small positive constant. The right side of inequality (1) ensures that if there is a communication link from $u$ to $v$ $(l_{uv} = 1)$, the transmission range assigned to node $u$ must be no less than $d(u, v)$. The left side ensures that if $u$’s transmission range is no less than $d(u, v)$, then there must be $l_{uv} = 1$. Adding $\epsilon$ to the first term of the left side is to ensure $l_{uv} = 1$ when $u$’s transmission range is exactly equal to $d(u, v)$. Otherwise, $l_{uv} = 0$ also holds the inequality, which is wrong. Minimizing the two terms of the left side is to ensure $l_{uv} = 1$ when the transmission range assigned to $u$ is more than twice of $d(u, v)$. Otherwise, $\sum_{i=1}^{K_u} t_{u}^i x_u^i - d(u, v) > d(u, v)$ and any value of $l_{uv}$ can not satisfy the inequality.

In addition, since each node has only one NIC and thus can be assigned one and only one power level, we have the following constraint:

$$\sum_{i=1}^{K_u} x_u^i = 1 \forall u \in V$$  \hspace{1cm} (2)

Finally, if symmetric communication is required in the network, two nodes can communicate with each other if and only if they locate within the transmission range of each other. This requirement induces one more constraint:

$$l_{uv} = l_{vu} \text{ (symmetric communication)}$$  \hspace{1cm} (3)

4.2 Flow Constraints

Let $f_{uv}$ denote the rate at which traffic is transmitted from node $u$ to node $v$ through the directed link $(u, v) \in E$, and $S (S \subset V)$ the set of non-gateway nodes. We would like each mesh router $u$ to send out the maximal possible amount of traffic, namely its traffic demand $\lambda_u$. However, this may not always be possible. In this case, we assume that only a certain percentage of its traffic demand, denoted by $\alpha_u$, is routed to the Internet.

Since each non-gateway router is also responsible to relay the traffic coming from other routers through its incoming links, the total traffic on its outgoing links must be equal to the sum of the traffic on its incoming links and its own outgoing traffic:

$$\sum_{w \in S} f_{uw} - \sum_{w \notin S} f_{uw} = \alpha_u \lambda_u \forall u \in S$$  \hspace{1cm} (4)

$$f_{uv} \geq 0 \forall u, v \in V$$  \hspace{1cm} (5)

$$0 \leq \alpha_u \leq 1 \forall u \in V$$  \hspace{1cm} (6)

The latter two constraints implicate that some communication links may not be chosen by the routing strategy ($f_{uv} = 0$) and some nodes may starve ($\alpha_u \approx 0$).

In addition, suppose the link capacity of link $(u, v) \in E$ is $C_{uv}$, then we must ensure that no link capacity is violated, and if there is no link from $u$ to $v$, there must be $f_{uv} = 0$:

$$f_{uv} \leq C_{uv} l_{uv} \forall u, v \in V$$  \hspace{1cm} (7)

Finally, for any non-gateway node $u$, all the traffic on its incoming links, its own outgoing traffic and the traffic on its outgoing links must pass through its NIC. However, it is equipped with only one NIC with the transmission capacity $B_u$. This fact imposes the following constraint:
\[ \alpha_u \lambda_u + \sum_{v \neq u} f_{uv} + \sum_{v \neq u} f_{vu} \leq B_u \quad \forall u \in S \quad (8) \]

With respect to gateways, the constraint above is still indispensible. However, since gateways are the destinations of traffic flows and thus have no outgoing links, this constraint can be simplified as follows:

\[ \alpha_u \lambda_u + \sum_{v \neq u} f_{vu} \leq B_u \quad \forall u \in (V - S) \quad (9) \]

4.3 Interference Constraint

Generally speaking, three main interference models are considered in wireless networks: the RTS/CTS interference model, the protocol interference model and the physical interference model. In this paper, we do not assume which model is applied in the network.

Let \( I_{uv} \) denote the set of links that can interfere with link \((u, v) \in E\). Under different interference model, \( I_{uv} \) may be different. However, once the interference model is decided, \( I_{uv} \) can be computed. Since links in \( I_{uv} \) can not transmit simultaneously with link \((u, v)\), we have the following interference constraint:

\[ f_{uv} + \sum_{(x,y) \in I_{uv}} f_{xy} \leq C_{uv} \quad \forall (u, v) \in E \quad (10) \]

This constraint holds for both uni-directed transmission and symmetric transmission pattern. However, the values of \( I_{uv} \) may be different in these two transmission patterns.

The above is the interference constraint when the network topology is given. However, the network topology can be decided only after the transmission power assignment is finished. Let \( N_{uv} \) denote the set of nodes that can not transmit simultaneously with node \( u \) or \( v \), i.e., \( N_{uv} = D(u, qP_u) \cup D(v, qP_v) \), where \( D(u, qP_u) = \{ w | d(u, w) \leq qP_u \} \). We have the following interference constraint by jointly considering the power assignment:

\[ \left( \sum_{y \in N_{uv}} (f_{uy} + f_{vy}) + \sum_{y \in N_{uv}} \sum_{y \neq v} (f_{xy} + f_{yx}) \right) I_{uv} \leq C_{uv} I_{uv} \quad \forall u, v \in V \quad (11) \]

Timing \( I_{uv} \) in both sides of the inequality is to ensure that this interference constraint is applicable to \((u, v)\) if and only if link \((u, v) \in E\) exists \( (I_{uv} = 1) \).

4.4 Objective

The objective in this paper is to maximize the network throughput that can be defined as one of the following ways:

- The total traffic from all routers which are finally routed to the Internet via gateways. In this case, the objective function will be:
  \[ \text{Max} \sum_{u \in V} \alpha_u \lambda_u \]

- The minimal percentage of traffic demand of each router which is actually routed to the Internet via gateways. Then the objective function will become:
  \[ \text{Max} (\min_{u \in V} \alpha_u) \]

For any non-gateway node \( u \), we can compute \( \alpha_u \) from Equation (4). However, with respect to gateways, \( \alpha_u \) must be computed by the following equation according to Constraint (9):

\[ \alpha_u = \min \left\{ B_u - \sum_{v \in N_{uv}} f_{vu} \right\} / \lambda_u, 1 \]

Now we can mathematically formulate the joint power control and routing problem with one of the above objectives subjected to the Topology Control Constraints (1) - (2) and (3), Flow Constraints (4) - (9) and Interference Constraint (11).

Obviously, the joint power control and routing problem is NP-complete. In order to reduce the computation cost to handle this NP-complete problem, we propose several heuristic algorithms. The basic idea is to decompose the joint problem into two sub-problems:

1. Topology control by transmission power assignment such that the total interference or the maximum node interference in the network is minimized.
2. Traffic routing on the obtained network topology by linear programming to maximize the total throughput or the minimal per-node throughput.

5 Topology Control and Traffic Routing

In this section, we first design two heuristic algorithms to assign transmission powers to mesh routers for the power control sub-problem, such that the total interference or the maximum node interference in the network is minimized. Next, we design two linear programming formulations for the routing sub-problem to maximize the total throughput or the minimal per-node throughput.

5.1 Topology Control for Min-Max Node Interference

In this subsection, we need to assign transmission power to each node such that the network topology can satisfy certain properties \( P \) while the maximal node interference is
minimized. The network properties $P$ can be considered as, but not limited to, that for each non-gateway node, there must be at least one directed path from this node to gateways.

In this section, we use protocol interference model in the network. The interference range is assumed to be $q$ times, which is typically between 2 and 4, of the transmission range. Then, any two directed links $(u, v) \in E$ and $(x, y) \in E$ can transmit simultaneously if and only if $d(x, v) > q_t$ and $d(u, v) > q_t^{-1}$. The weight of the directed link $(u, v)$ is assigned as $\omega(u, v) = \chi_u^k$. Therefore, all outgoing links of $u$ can be divided into $K$ groups, each directed link of $k^{th}$ group is assigned with the same weight $\chi_u^k$. Note that maybe some group is empty.

**Definition 1 (Node Interference)** Let $u$ be any node in $G$. The node interference of $u$ at power level $k$, denoted by $\chi_u^k$, is defined as the number of nodes that can be interfered by $u$:

$$\chi_u^k = | \{ x \mid d(u, x) \leq q_t^k \} |$$

We design an optimal algorithm (Fig. 1) that assigns each router a transmission power to minimize the maximal node interference. The basic idea is to construct a directed graph as follows. A directed link $(u, v)$ exists between node $u$ and $v$ if and only if $u$ can transmit to $v$ on a certain power level, and $\chi_u^k$ is assigned as the link weight of $(u, v)$, where $q_t^k$ is the smallest power level that enables $u$ to transmit to $v$. Then we use a binary search to find the optimal topology that the maximal node interference is minimized.

Suppose $\omega$ is the minimal feasible weight computed by the algorithm in Fig. 1, then we can assign the power level to each node according to $\omega$. The network topology $G_\omega$ can be constructed according to $\omega$ as follows: $G_\omega$ only includes the links whose weight is no more than $\omega$. For each node $u$, we can decide its optimal power level $p_u$ by the maximum weight of all out links of $u$ in $G_\omega$. That is, if the maximum weight of all out links of $u$ in $G_\omega$ is $\chi_u^k$, then $u$’s power level is $p_u^k$ by definition 1.

5.2 Topology Control for Min Total Interference

We apply a maximal interference decremental method (similarly we can apply the minimal interference incremental method) to construct the topology with minimal total interference in the network. Suppose the network topology when all nodes use the maximal power level is denoted by $G_{max} = (V, E_{max})$. We formalize the following concepts:

**Definition 2** Let $u$ be any node in $G_{max}$. The Increased Interference and Increased Link Set of node $u$ at power level $k$, denoted by $\Delta_u^k$ and $E_u^k$ respectively, are defined as:

$$\Delta_u^k = | \{ x \mid q_t^{k-1} < d(u, x) \leq q_t^k \} |$$

$$E_u^k = | \{ (u, v) \mid d(u, v) > q_t^k \} |$$

**Step 1** Construct an auxiliary directed graph $G_{max} = (V, E_{max})$. For each node $u \in V$, a directed link $(u, v)$ belongs to $E_{max}$ if $\exists k (1 \leq k \leq K_u)$ such that $d(u, v) < q_t^k$ and $d(u, v) > q_t^{k-1}$. The weight of the directed link $(u, v)$ is assigned as $\omega(u, v) = \chi_u^k$. Therefore, all outgoing links of $u$ can be divided into $K$ groups, each directed link of $k^{th}$ group is assigned with the same weight $\chi_u^k$. Note that maybe some group is empty.

**Step 2** Sort all groups of links in step 1 in ascending order according to their weight. Suppose the result is $\omega_1 \leq \omega_2 \leq \ldots \leq \omega_n$, where $n$ is number of different groups of links $n < |E_{max}|$. Then begin to binary search:

1: low = 1 and up = n
2: while low <= up do
3: mid = $\lfloor\frac{low + up}{2}\rfloor$
4: Construct a subgraph $G_{max}$ that only includes all links whose weight is no more than $\omega_{mid}$ in $G_{max}$
5: if $G_{max}$ satisfies property $P$ then
6: up = mid - 1
7: else
8: low = mid + 1
9: end if
10: end while

**Figure 1. Min-Max Topology Control Algorithm**

The algorithm is presented in Fig. 2. The basic idea is that all nodes are first sorted in descending order of $\Delta_u^k$, which is the increased interference of node $u$ at its highest so-far power level $h$. Then, we check whether $G_{max}$ still satisfies property $P$ after removing $E_u^h$ from $G_{max}$. If the answer is positive, we remove $E_u^h$ from $G_{max}$; otherwise, it means node $u$ cannot reduce its power level anymore, and thus we remove $u$ from the node set. Repeat this process until the node set becomes empty. After this algorithm is executed successfully, we can assign each node $u$ to power level $p_u$ and the final network topology will be $G_{max}$ when this algorithm is finished.

5.3 Traffic Routing

As long as the network topology has been obtained from the algorithm in Fig. 1 or Fig. 2, we can decide the traffic routing by LP formulation only subjected to Flow Con-
Since both LP1 and LP2 are linear programming formulations, the optimal solutions can be obtained.

5.4 Joint Power Control and Traffic Routing

In previous subsections, we have proposed two topology control algorithms, one for minimizing maximal node interference and the other for maximizing the total interference. We also proposed two traffic routing approaches, one for maximizing minimal per-node throughput and the other for maximizing total throughput. Based on these solutions, we can solve the joint power control and routing problem as described in Fig. 3:

Step 1 Obtain a network topology using the algorithm in Fig. 1 or Fig. 2.
Step 2 Find the traffic routing by computing LP1 or LP2 on the topology obtained from Step 1.

6 Numerical Results

In this section, we evaluate the performance of our algorithms via simulations. We consider static wireless mesh networks with n nodes randomly located in a 200 x 200m² region, and a certain percentage of these nodes are selected randomly as gateways. Each node has 10 different power levels (K = 10) and the differential transmission range of adjacent power levels is 5m, while the minimal transmission range (power level 1) is also 5m. In addition, the interference range is assumed to be 2 times of the corresponding transmission range (q = 2). The transmission capacity of each node is fixed to be 30 Mbps (B = 30 Mbps) and the traffic demand to be 10 Mbps (λ = 10 Mbps) when measuring Max-total throughput and 7.5 Mbps (λ = 7.5 Mbps) when measuring Max-min throughput respectively. Finally, we assume a simple wireless channel model in which link rates depend only on the distance between the two nodes consisting this link. According to IEEE 802.11 specifications, we assume that the link rate when the two mesh nodes are within 30 meters is 54 Mbps, 48 Mbps when within 32 meters, 36 Mbps when within 37 meters, 24 Mbps when within 45 meters and 18 Mbps when within 60 meters.
Based on the algorithm described in Fig. 3, we test four different combinations of the algorithms designed for the two sub-problems, i.e. LP1 on Min-total topology (Fig. 2), LP1 on Min-max topology (Fig. 1), LP2 on Min-total topology and LP2 on Min-max topology. The linear programs in our algorithm are solved using MATLAB (Version R2006b). For each combination, we generate 10 networks as described at the beginning of this section and take the average of these 10 results as the final performance. Different performance aspects of these four combinations are investigated under four scenarios.

In the first scenario, we measure the total network throughput under different node densities and the simulation results are reported in Fig. 4. We vary the nodes number N from 20 to 250 and 10 percent of these nodes are gateways. The following observations can be made according to our simulation result.

First, Min-total topology always has higher total throughput than Min-max topology. The reason is that interference is the main factor which decreases the total throughput of the network. As Min-total topology has smaller number of total interference, its total throughput is higher.

Second, as the nodes number increases, the total throughput increases correspondingly (Fig. 4a). However, when the node density reaches a certain level (about when \( N = 120 \)), the increase speed slows down. This problem can be explained more clearly in Fig. 4b. We can divide the total throughput into two parts: one is due to the transmission of gateways, and the other is contributed by non-gateway nodes. As the node density increases, the interference also increases and consequently the increased throughput of the latter part becomes smaller (refer to Constraint (10)). When the node density reach a certain level, the test area becomes saturated (about when \( N = 200 \)) and the latter part stops increasing due to the limited channel capacity. In this situation, the increased total throughput is totally contributed by the transmission of the new added gateways, because their traffic can reach the Internet directly.

In the second scenario, we test the total network throughput under different gateway ratios and the simulation results are reported in Fig. 5. The gateways ratio is varied from 5% to 80% and the nodes number \( N \) is fixed to 100.

Similar to the results of the first scenario, Min-total topology always has higher total throughput than Min-max topology. However, the differential throughput increases at the beginning, but begins to decrease when the gateway ratio reach a certain level (at about 30%). Finally, these two topologies will have the same total throughput, with all traffic routed to the Internet (Fig. 5a). The reason can be drawn from Fig. 5b, which shows the percentage of traffic load finally routed to the Internet of non-gateway nodes. While the increased throughput of gateways is nearly equal as the gateways ratio increases in these two topologies, the served traffic ratio of non-gateway nodes increases nearly linearly in Min-total topology. However, this ratio increases very slowly at the beginning, but begins to speed up later in Min-max topology. The reason is that as the gateways ratio increases, non-gateway nodes are more likely to connect to some nearby gateways using small transmission powers. Consequently, the number of total interference of Min-max topology will approach that of Min-total topology.

In the third scenario, we investigate the minimal \( \alpha_v \), under different node densities and the simulation result is reported in Fig. 6. We vary the nodes number \( N \) from 10 to 80 and 10 percent of these nodes are gateways. We can obtain the
following observations based on this simulation result.

First, Min-max topology always outperforms Min-total topology in this scenario. When we try to minimize the total interference, some “unfortunate” nodes may suffer from severe interference, which will degrade their performance. However, the performance of these nodes will decide the value of minimal $\alpha_v$. Furthermore, while total interference of Min-max topology is bigger than that of Min-total topology, more transmission links are available as well, based on which a better routing strategy can be achieved.

Second, we can divide this result into three parts. At the beginning ($N \leq 30$), the value of minimal $\alpha_v$ decreased sharply since total interference in the network will increase quickly as the node density increases. In the second part ($30 < N \leq 60$), this value only reduces slightly. The reason is that although total interference increases in this phase as well, each node is more likely to connect to gateways via nearby nodes by using lower transmission power. In addition, transmission links increase quickly as well. As a result, throughput reduction caused by increased interference can be compensated by routing on increased available links. However, as the nodes number continues to increase ($N > 60$), the test area will approach its saturated status. Then the channel capacity will become the bottleneck and similar thing will happen as shown in Fig. 4b. Consequently, this value will decrease continuously.

According to our simulation results, we can conclude that the total interference should be minimized if we want to maximize the total throughput, and the maximal node interference should be minimized if we want to maximize the minimal per-node throughput.

7 Conclusion and Future Work

In this paper, we study the joint power control and routing problem in WMNs to maximize the network throughput. First, we mathematically formulate this problem. Next, we decompose this joint problem into two sub-problems and handle the joint problem by the solutions designed for them. Our simulation result reveals that topology control should be carried out according to different network throughput considerations.

Our future work is to study the throughput optimization with different QoS requirements. Because WMNs should provide different kinds of service, such as VoIP service, multimedia service and file transfer, which have different QoS requirements. Distributed algorithms are also of our interests.

References