A Novel Gateway Selection Technique for Throughput Optimization in Configurable Wireless Mesh Networks

Citation:

Wei Liu, Hiroki Nishiyama, Nei Kato, Yoshitaka Shimizu, and Tomoaki Kumagai, "A Novel Gateway Selection Technique for Throughput Optimization in Configurable Wireless Mesh Networks," International Journal of Wireless Information Networks, vol. 20, no. 3, pp. 195-203, Sep. 2013.

URL:

http://link.springer.com/article/10.1007/s10776-013-0203-y

Noname manuscript No.
(will be inserted by the editor)

A Novel Gateway Selection Technique for Throughput Optimization in Configurable Wireless Mesh Networks

**Wei Liu · Hiroki Nishiyama · Nei Kato ·
Yoshitaka Shimizu · Tomoaki Kumagai**

Received: date / Accepted: date

Abstract Wireless mesh networks (WMNs) have attracted much attention due to their low up-front cost, easy network deployment, stable topology, robustness, reliable coverage, and so forth. These advantages are suitable for the disaster recovery applications in disaster areas, where WMNs can be advantageously utilized to restore network collapse after the disaster. In this paper, based on a new network infrastructure for WMNs, to guarantee high network performance, we focus on the issue of throughput optimization to improve the performance for WMNs. Owing to selecting different mesh router as the gateway will lead to different network throughput capacity, we propose a novel gateway selection technique to rapidly select the optimal mesh router as the gateway, in order to maximize the network throughput. In addition, we take into account the traffic distribution for the mesh router to eliminate traffic congestion in our method. The performance of our proposed method is evaluated by both numerical and simulated analysis. The simulation results demonstrate that the gateway selection method is effective and efficient to optimize the throughput for wireless mesh networks.

Keywords Wireless Mesh Networks (WMNs) · Throughput optimization · Gateway selection · Traffic congestion.

W. Liu, H. Nishiyama, and N. Kato
Graduate School of Information Sciences, Tohoku University, Aobayama 6-3-09, Sendai, 980-8579, JAPAN.
Tel.: +81-22-795-4287
Fax: +81-22-795-4903
E-mail: {liuwei,bigtree,kato}@it.ecei.tohoku.ac.jp

Y. Shimizu, T. Kumagai
NTT Network Innovation Laboratories, NTT Corporation, Yokosuka, JAPAN.
E-mail: {shimizu.yoshitaka, kumagai.tomoaki}@lab.ntt.co.jp

1 Introduction

Wireless Mesh Networks (WMNs) are a quickly emerging technology for last mile broadband Internet access, which have attracted lots of intensive attention in recent years, due to their various significant advantages [1], [2], [3], such as low up-front cost, easy network deployment, stable topology, robustness, reliable coverage, and so forth. Moreover, WMNs inherit the typical characteristics from the ad hoc network paradigm, with the capability of self-forming, self-healing, and self-organization. These features and advantages are very feasible to various applications, especially suitable for disaster recovery. We know that natural disasters (e.g., earthquake, tsunami, and typhoon, etc.) occur frequently over the years in the worldwide, which cause the destruction of a large number of communication equipments (e.g., base station, wireless router, etc.) and the communication interrupt so that people cannot timely contact with the outside world. For example, recent disaster events such as 3-11 East-Japan earthquake that destroyed almost available communication devices, seriously showed that the remaining functional parts of the network were unable to provide adequate services to satisfy people's requirement. Therefore, fast recovering the resilient network and guaranteeing high network performance are crucial in disaster areas.

Nowadays research in the field of WMNs has been aimed on throughput capacity to guarantee high network performance. Throughput is one of major evaluated standards for network performance [4], [5], [6], [7]. However, due to all the nodes having to send the packets to the gateway for Internet access, different node served as the gateway will significantly affect the throughput capacity in the network. Therefore, we should take into account the problem of gateway selection to determine the optimal node as the gateway, in order for improving network throughput capacity.

After the disaster, people would like to communicate with the outside world immediately by transmitting packets to the gateway via multi-hop mesh routers for Internet access. The explosive increase of communication demands are required. A lot of packets in the queue of the mesh router are waiting for transmitting. However, it should be noted that the more offered load cannot guarantee the higher throughput capacity. In other words, as the offered load increases, it will lead to the high proportion of traffic congestion during the transmission links, so as to degrade the transmission efficiency. In the reference [6], it has analyzed the impact of the throughput on the offered load. The results demonstrated that the throughput is first increasing with the offered load until it arrived at the peak value, and then gradually decreases with the offered load increasing. As a consequence, in our gateway selection method, we should also take account of controlling the traffic from the mesh router to the gateway, in order to alleviate the congestion and optimize the network throughput.

In this paper, we mainly focus on the issue of how to manage the wireless mesh network to fast and efficiently select the optimal mesh router as the gateway and adjust the appropriate traffic for the node, in order to optimize network throughput capacity. To solve this problem, we propose a gateway selection method for throughput optimization in wireless mesh networks. The main contributions of the paper are as follows:

- In contrast to the conventional method that every mesh router in the network is regarded as the candidate gateway to respectively calculate the throughput with extremely high computational complexity, we propose a novel gateway selection algorithm to significantly reduce the computing complexity and increase the efficiency, which is able to determine the optimal node as the gateway to maximize the throughput access to the Internet.
- Based on the selected gateway node, we make use of the upper bound throughput to distribute and balance the traffic for the mesh router transmitting to the gateway, in order to avoid congestion whenever possible, and optimize the throughput capacity in the network.

The remainder of this paper is organized as follows. Section 2 introduces an example of WMN infrastructure deployed in real environment in Japan and presents our network model to define the backbone network. We devote Section 3 to present a novel gateway selection technique to effectively select the gateway node and adjust the traffic for the mesh router to optimize the throughput in the network. In Section 4, we evaluate the performance of our proposed technique. In Section 5, we give an overview of related works on throughput capacity analysis techniques in WMNs. Finally, we conclude the paper in Section 6.

2 System Model

To optimize the network throughput, system model is critical that requires efficient gateway and traffic allocation. In this section, we first describe an example of the infrastructure for the wireless mesh network designed by considering an actual disaster scenario in Japan. Moreover, we discuss the network model for the backbone wireless mesh network.

2.1 Wireless mesh network infrastructure

After the 3-11 earthquake, people attempted to communicate with their family and friends for safety confirmation by the communications devices. The resilient network is need to urgent resolution after the damaged network as soon as possible. Currently, lots of researches are devoting to the problem of quickly recovering communications in disaster areas. Here, there is a new network infrastructure for a real environment [8]. As shown in Fig. 1, it illustrates an example of the WMN infrastructure designed by considering an actual disaster area. The infrastructure is divided into three hierarchies. A Movable and Deployable Resource Unit (MDRU) is located in the center of the area as the top hierarchy. The MDRU is a transportable container, which

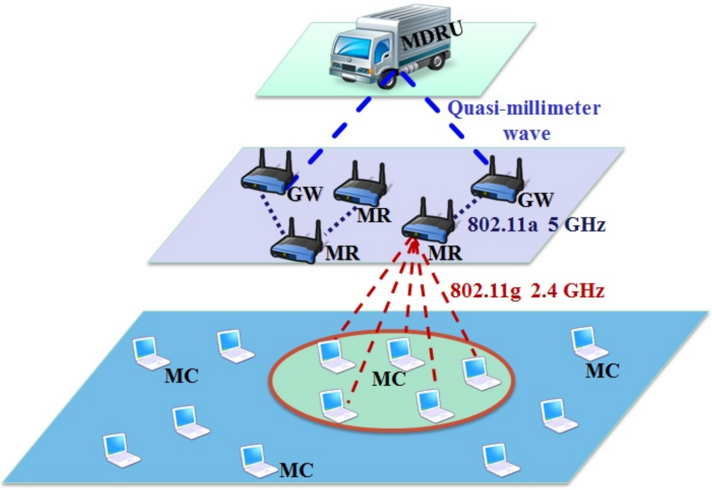

Fig. 1 An example of the infrastructure for wireless mesh networks.

provides modularized equipment for networking, information processing, and storage. Once the disaster occurred, it can be rapidly transported to disaster areas and construct a resilient network to provide Internet connectivity, which it is in charge of remoting control the Mesh Routers (MRs) in the damaged zone, involving monitoring the transmission load, adjusting the traffic rate, and so forth. Particularly, it sets up the connection to the gateway with quasi-millimeter wave band, keeping them for accessing the Internet. In the middle hierarchy, the mesh routers make up the backbone network, playing the role of not only transmitting but also forwarding the packets to the gateway so as to exchange the information with the Internet by 802.11a with 5 GHz band. In addition, note that the GateWay (GW) is a specific mesh router that directly connects to the MDRU, which is responsible to relay the packets to the Internet. Selecting different mesh router as the gateway leads to different network throughput capacity. In what follows we will detailedly present how to select the mesh router as the gateway to optimize the throughput in the backbone network. The bottom hierarchy consists of the Mesh Clients (MCs), which contact to the mesh routers by 802.11g with 2.4 GHz band.

2.2 Network model

Suppose that the link has enough bandwidth to forward overall data from the gateway to the MDRU. Thus, in this paper, we only concentrate our attention on the backbone network that is mainly used as access networks for sending/receiving information to/from the mesh clients via wireless mesh routers. We take into account the backbone network model to analyze the throughput optimization. Since the backbone network comprises of mesh routers, unless mentioned otherwise, we use the term “node” referred as the mesh router in the following.

To design the backbone network model, various factors need to be considered, such as network architecture, routing algorithm, channel, size, topology, etc. In this section, we first take into account the model as the general network, where nodes are randomly normal distribution. Moreover, assume that a set of nodes are deployed in a certain area. It is defined as a graph $G = (V, E)$, where $V = v_1, ..., v_n$ represents the set of mesh routers, and E is the set of communication links. Let $l_{i,j}$ denote the link from node v_i to node v_j. $L_{i,j}$ denotes the traffic of $l_{i,j}$. In this model, each node v_i has a traffic demand $TD(v_i)$ that represents the total traffic from the clients waiting to transmit. In addition, each node has the same transmission range where node v_j is able to receive data correctly from v_i when it is within v_i's transmission range. And each node also has the same interference range.

In this model, we assume that only one gateway node is deployed in the network. If there are multiple gateways, the problem can be solved by separating the nodes related to one gateway from nodes associated to other gateways, which is out of the research in this paper. Each node can send and receive packets directly to and from other nodes within its transmission range. The nodes are fixed at a location in the network.

Routing path is an essential factor to influence the performance of wireless mesh network. We know that selecting different routing to transmit the packet will result in different network throughput capacity. Thus, we take into account unique routing path in our network model, where it utilizes the Minimize Spanning Tree (MST) algorithm to set up the routing path from the node to the gateway.

3 Gateway Selection Technique

In this section, we analyze the throughput capacity for wireless mesh networks, and propose a novel algorithm that can effectively select the optimal node as the gateway to maximize the network throughput.

3.1 Analyze the network throughput

For estimating network throughput capacity, there are two important factors, the Bottleneck Collision Domain (BCD) and the Theoretical Maximum Throughput (TMT), which crucially influence on the network throughput.

3.1.1 Bottleneck collision domain

According to the literatures [9], [10], if we want to optimize the throughput, one of the most important thing is to prevent collision happening. From Fig. 2, there are 8 nodes (v_1, ..., v_8) constructed a chain model, where the nodes

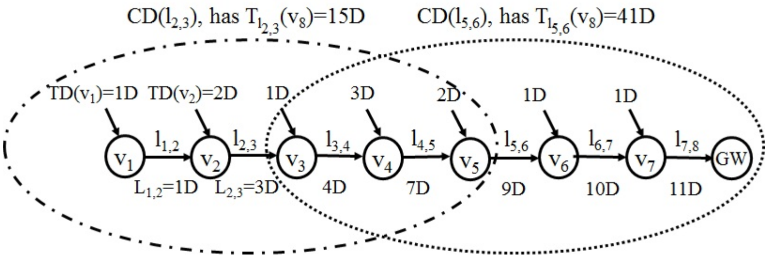

Fig. 2 Illustration of collision domains.

transmit the packet to the gateway (node v_8 is as the gateway). When two links are adjacent enough to interfere with each other, the packets cannot be transmitted via the two links simultaneously. It will result in a collision. For example, if node v_3 sends a packet to the gateway while node v_5 is transmitting, it will generate collision so that both transmissions fail. Therefore, to avoid collision, we should try to maintain only one node that it is permitted to transmit packets at a time in a certain region, where is enclosed according to the interference range of the active nodes. In practice, when node v_5 is sending packet to v_6 (link $l_{5,6}$), node v_3, v_4, v_7 and the gateway v_8 can sense its current status, but not node v_1 and v_2. Therefore, node v_1 and v_2 can send the packet even if v_5 is transmitting simultaneously, where they do not interfere with the transmission of link $l_{5,6}$. In other words, $l_{5,6}$ can send successfully if and only if nodes inside the interference range (v_3, v_4, v_7 and v_8) keep inactivity state. Consequently, we can estimate the collision domain of link $l_{5,6}$ that is enclosed by a dashed circle (including $l_{3,4}$, $l_{4,5}$, $l_{5,6}$, $l_{6,7}$, and $l_{7,8}$) as shown in Fig. 2.

Therefore, the collision domain of link $l_{x,y}$, $CD(l_{x,y})$, is defined as a range that encloses a set of wireless links to avoid collision. The traffic in the $CD(l_{x,y})$ when node v_i is as the gateway, $T_{l_{x,y}}(v_i)$, is mainly related to the interference range and the traffic of each node. As shown in Fig. 2, assume that the interference range is two times over the transmission range and each node has the different traffic demand ($TD(v_1) = 1D, TD(v_2) = 2D, TD(v_3) = 1D, TD(v_4) = 3D, TD(v_5) = 2D, TD(v_6) = 1D, TD(v_7) = 1D$) to send to the gateway. Note that the collision domain has to transmit all traffic of the links within its domain. Therefore, the total traffic in the $CD(l_{5,6})$ is equal to the summation of $L_{3,4}$, $L_{4,5}$, ..., $L_{7,8}$, i.e., $T_{l_{5,6}}(v_8) = 41D$, when all traffic flow toward the gateway node v_8. In doing so, we can get the value of traffic in other links' collision domain, e.g., the traffic in the collision domain of $l_{2,3}$, $T_{l_{2,3}}(v_8)$, is equal to $15D$. Herein, it should be noted that the traffic in a collision domain of a certain link is a function of which node is the gateway, because the traffic flow direction changes with the location of gateway.

In summary, the bottleneck collision domain is defined as the collision domain that has to forward the most traffic among all links in the network. According to the obtained values for each link in Fig. 2, we can clearly see that the collision domain of $l_{5,6}$ has the largest traffic as the Bottleneck Collision Domain (BCD) in this model.

3.1.2 Theoretical maximum throughput

To track the issue of calculating available throughput capacity, another important factor that influence the network throughput is the Theoretical Maximum Throughput (TMT) [11], which is defined as the maximum available transmission throughput on the MAC layer according to the theoretical analysis. The theoretical maximum throughput is calculated based on 802.11 standards [11], [12], [13], [14], where there are various parameters, such as physical layer and MAC layer variations, packet size, basic data rates, etc. TMT can be calculated by the equation:

$$TMT = \frac{\text{(MSDU Size)}}{T_{delay}}, \tag{1}$$

where MAC Service Data Unit (MSDU) denotes a packet pushed from the higher layer down to the MAC layer, and T_{delay} is the consumed time for transmitting per MSDU packet, which consists of several components, such as Short Inter Frame Spacing (SIFS), Acknowledgment (ACK), Distributed Inter Frame Spacing (DIFS), Request To Send (RTS), Clear To Send (CTS), BackOff (BO), and payload size. The values of these parameters can be obtained from the IEEE standard [12], [13], [14]. As a consequence, we can get the exact result of the theoretical maximum throughput.

3.1.3 Upper bound throughput

After knowing the theoretical maximum throughput and bottleneck collision domain, we can estimate the upper bound throughput by using these two factors, which denotes the available maximum traffic demand via the link to guarantee successfully transmitting the traffic without congestion. Note that, due to the collision domain corresponding to each link cannot forward more than the theoretical maximum throughput, we can calculate the upper bound throughput as follows:

$$D_{max} = \frac{TMT}{\text{(Traffic in BCD)}}. \tag{2}$$

This formulation for calculating the upper bound capacity of a chain network can be extended to arbitrary topologies.

3.2 A novel gateway selection algorithm

3.2.1 Motivation

As mentioned above, we can estimate the throughput capacity as long as the network topology fixed. Since different node assigned as the gateway brings the different traffic in its bottleneck collision domain, it will lead to different upper bound throughput result. In this paper, we mainly focus on the problem of

Table 1 Parameters in the system model.

Parameter	Description
$\forall v_x \in V$	A set of nodes v_x in V, $\forall x \in N$
$\forall l_{x,y} \in E$	A set of links $l_{x,y}$ in E, $\forall x, y \in N$
$G = (V, E)$	A garph G
v_x	A mesh router in the network
$l_{x,y}$	The link from node v_x to node v_y
$L_{x,y}$	The traffic of link $l_{x,y}$
$TD(v_x)$	The traffic demand of node v_x
$CD(l_{x,y})$	The collision domain of link $l_{x,y}$
$T_{l_{x,y}}(v_i)$	The total traffic in collision domain of link $l_{x,y}$ when node v_i is as the gateway

Table 2 Illustration of the design motivation.

	$CD(l_{1,2})$	$CD(l_{2,3})$	...	$CD(l_{x,y})$	...
v_1	$T_{l_{1,2}}(v_1)$	...	...	$T_{l_{x,y}}(v_1)$	...
v_2	...	...	...	$T_{l_{x,y}}(v_2)$	...
...	...	...	...	...	...
v_i	$T_{l_{1,2}}(v_i)$	$T_{l_{2,3}}(v_i)$	...	$T_{l_{x,y}}(v_i)$	...
...	...	...	...	...	...

gateway selection to optimize the throughput in the network. Note that, due to the TMT is a constant value as long as 802.11 standard is decided, the smaller the traffic in the bottleneck collision domain, the larger the network throughput. Therefore, we would like to select the node as the gateway among all nodes from the network, which has the smallest traffic in its bottleneck collision domain.

To find the optimal node by the conventional method, we have to calculate the traffic in the bottleneck collision domain for each node as the gateway, it needs high computation complexity. In our new proposal, it will have low computation complexity to efficiently select the optimal node (The parameters in our model are summarized in Table. 1). Note that each link has the same collision domain whatever node is the gateway. Take Table 2 for example, when the given node v_i is as the tentative gateway, we can get $CD(l_{x,y})$ has the maximum traffic $T_{l_{x,y}}(v_i)$ among all collision domain as the bottleneck collision domain. We then compare the traffic in $CD(l_{x,y})$ for other nodes as the gateway with $T_{l_{x,y}}(v_i)$. If the traffic in $CD(l_{x,y})$ for the given node is larger than $T_{l_{x,y}}(v_i)$, the node cannot be as the gateway. This is because, when a node is as the gateway, the traffic in bottleneck collision domain is larger than the traffic in other collision domains (i.e., if $T_{l_{x,y}}(v_1) > T_{l_{x,y}}(v_i)$, the traffic in v_1's bottleneck collision domain is larger than $T_{l_{x,y}}(v_1)$, namely, it is larger than $T_{l_{x,y}}(v_i)$). On the contrary, if the traffic in $CD(l_{x,y})$ for the node is less than $T_{l_{x,y}}(v_i)$, it will be as the candidate gateway, because we cannot compare the size of the traffic in its bottleneck collision domain with $T_{l_{x,y}}(v_i)$. As a consequence, we can efficiently reduce the candidate range and the computation complexity.

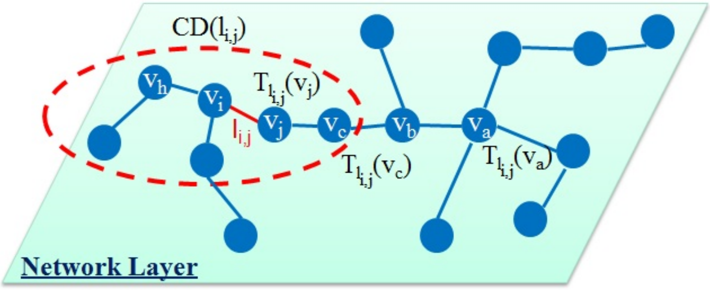

Fig. 3 Illustration of the proposal for general scenario.

3.2.2 Proposal

In this section, we will detailedly present a novel gateway selection algorithm that is able to choose the optimal node as the gateway to maximize the network throughput with high efficiency and low computation complexity. The following description is based on the example depicted in Fig. 3.

Step 1: We first select the node v_a as the tentative gateway randomly. We can get the collision domain of $l_{i,j}$ as the bottleneck collision domain, which includes the maximum traffic $T_{l_{i,j}}(v_a)$.

Step 2: We know that the traffic in $CD(l_{i,j})$ for the right nodes of node v_j are all equal to $T_{l_{i,j}}(v_a)$, i.e., $T_{l_{i,j}}(v_c) = T_{l_{i,j}}(v_b) = ... = T_{l_{i,j}}(v_a)$. In addition, we can get the traffic in $CD(l_{i,j})$ when node v_j is as the gateway, i.e., $T_{l_{i,j}}(v_j)$.

Step 3: Next, we compare the size of $T_{l_{i,j}}(v_j)$ and $T_{l_{i,j}}(v_a)$, namely, compare the size of $T_{l_{i,j}}(v_j)$ and $T_{l_{i,j}}(v_c)$. If $T_{l_{i,j}}(v_j)$ is larger than $T_{l_{i,j}}(v_c)$, node v_j is impossible as the optimal gateway in the network.

Step 4: When $T_{l_{i,j}}(v_j)$ is larger than $T_{l_{i,j}}(v_a)$, the traffic in $CD(l_{i,j})$ for the following nodes behind node v_j are all larger than $T_{l_{i,j}}(v_a)$ (the proof is shown in Section 3.2.3), so these nodes cannot be as the gateway in the network.

Step 5: On the contrary, if $T_{l_{i,j}}(v_j)$ is less than $T_{l_{i,j}}(v_c)$, v_j is regarded as the candidate gateway. Moreover, we continue to compare the next node following v_j, like node v_i, until finding a node that its traffic in $CD(l_{i,j})$ is larger than $T_{l_{i,j}}(v_c)$.

Step 6: After that, we can decide a few nodes as the candidate gateway. We go back to the Step 1 to loop this algorithm until only one node left. This node is the optimal node that serves as the gateway in the network, which has the smallest traffic in its bottleneck collision domain.

By using our proposed algorithm, it is able to not only quickly select the optimal node served as the gateway to guarantee the maximum network throughput, but also effectively reduce the computation complexity. We know that the conventional method has to calculate the traffic in the bottleneck collision domain for each node as the gateway respectively, then decide the optimal node with the corresponding smallest traffic in its bottleneck collision domain as the gateway. Its computation complexity is $O(n^3)$, since it has $O(n^2)$ to calculate the traffic in the bottleneck collision domain for one node. In contrast to the conventional method, we make use of the proposed gateway selection technique to effectively reduce the number of candidate nodes, with no need to calculate the traffic for all nodes in the network. The complexity $O(Cn^2)$ $(C \ll n)$ is much smaller than the conventional method.

After determining the gateway node, each mesh router regulates the traffic from their clients to the mesh tier according to the determined upper bound, D_{max}. As mentioned above, the MDRU is capable of monitoring and remoting control the traffic from each node to the gateway in our infrastructure. Based on the calculated upper bound throughput, we can control the traffic from the node to the gateway, in achieving throughput optimization.

3.2.3 Theorem

Therom 1: Based on the collision domain of the link $l_{i,j}$, when the traffic in $CD(l_{i,j})$ for the node v_j is larger than the traffic in the bottleneck collision domain for node v_a, the traffic in $CD(l_{i,j})$ for node v_j's following nodes are all larger than the traffic in the bottleneck collision domain for the given node v_a.

Proof: According to Fig. 3, suppose that $CD(l_{i,j})$ has the largest traffic when node v_a is as the tentative gateway, so $CD(l_{i,j})$ is the bottleneck collision domain for node v_a and the traffic in $CD(l_{i,j})$ is equal to $T_{l_{i,j}}(v_a)$.

By using the same $CD(l_{i,j})$, we know that $T_{l_{i,j}}(v_a) = T_{l_{i,j}}(v_c)$ and the traffic in $CD(l_{i,j})$ for node v_i and v_j are $T_{l_{i,j}}(v_i)$ and $T_{l_{i,j}}(v_j)$, respectively. Then, we can find the difference between $T_{l_{i,j}}(v_j)$ and $T_{l_{i,j}}(v_c)$, where there is only one different link traffic that is the opposite link between node v_j and v_c,

$$T_{l_{i,j}}(v_j) - T_{l_{i,j}}(v_c) = L_{c,j} - L_{j,c}. \tag{3}$$

In doing so, the difference between $T_{l_{i,j}}(v_i)$ and $T_{l_{i,j}}(v_j)$ can be obtained by the following equation:

$$T_{l_{i,j}}(v_i) - T_{l_{i,j}}(v_j) = L_{j,i} - L_{i,j}. \tag{4}$$

Following the direction of the traffic from source to gateway, note that the traffic of the front link is less than the traffic of back link, i.e., $L_{j,i} = L_{c,j} + TD(v_j)$. So, we know that

$$L_{j,i} > L_{c,j}, \tag{5}$$

$$L_{j,c} > L_{i,j}. \tag{6}$$

Because $T_{l_{i,j}}(v_j) > T_{l_{i,j}}(v_a)$, we can infer that

$$\begin{gathered} T_{l_{i,j}}(v_j) > T_{l_{i,j}}(v_c), \\ T_{l_{i,j}}(v_i) > T_{l_{i,j}}(v_j) > T_{l_{i,j}}(v_a). \end{gathered} \tag{7}$$

As a consequence, in this way, we can demonstrate that the traffic in the bottleneck collision domain for the following nodes of node v_j are all larger than $T_{l_{i,j}}(v_a)$ by recursion.

Table 3 Simulation parameters.

Parameter	Value
Simulator	Qualnet 5.1
Mobility model	Stationary
Terrain dimensions	700m x 700m
Protocol	802.11a
Basic data rate	54Mbps
Packet size	1500Bytes
T_{max}	26.8Mbps
Transmission range	100m

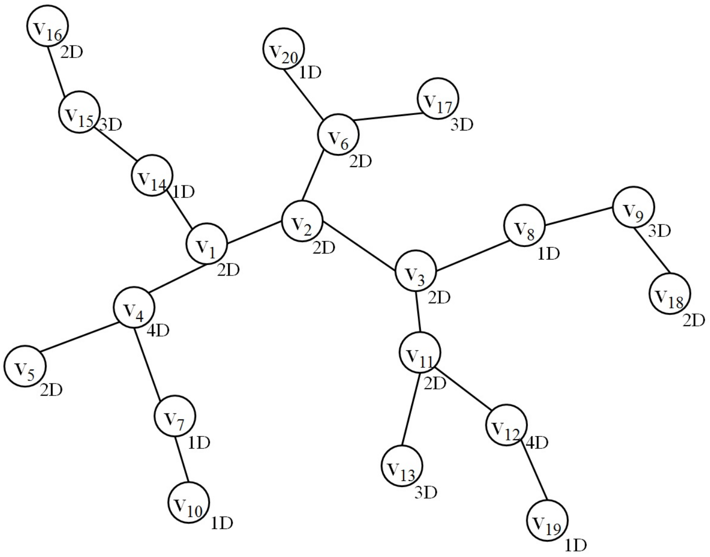

Fig. 4 An example of wireless mesh network topology used for simulations.

4 Performance Evaluation

To validate the performance of our porposed technique, we conducted simulations by using Qualnet 5.1 [15]. We observe the transmissibility in terms of adjusting the traffic for the mesh router to achieve throughput optimization.

4.1 Parameter settings

We take account of a disaster area within 700m by 700m constructed by a wireless mesh network, where each mesh router is deployed randomly (as shown in Fig. 4), and transmits and forwards packets with 802.11a with 54Mbps bandwidth. The packet size for transmission is set to 1500bytes, so the theoretical maximum throughput TMT can be calculated as 26.8Mbps [11]. We assume that all nodes are stationary in the network, and all of the traffics are transmit-

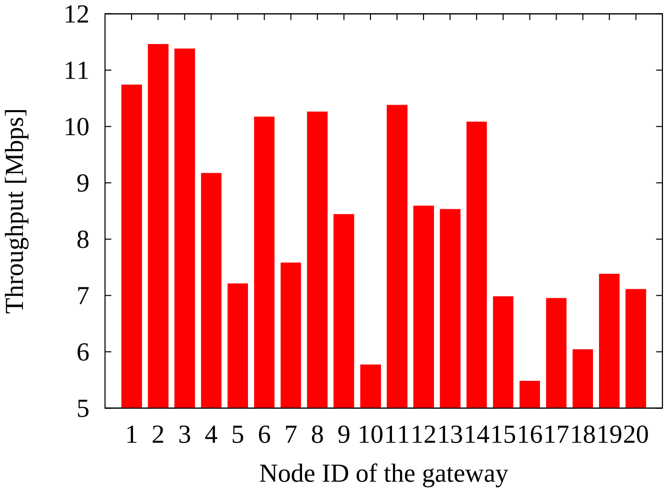

Fig. 5 Comparison of the network throughput when each node is served as the gateway respectively.

ted to the gateway. The transmission range of each node is set to 100 meters and the interference range is two times over the transmission range, where the node is allowed to communicate only with the neighboring nodes. The specific parameter settings are listed in Table 3. By running simulations with different network topologies and different traffic demands, it has been observed that the our gateway selection scheme perfectly selected the optimal mesh router as a gateway, which succeeded in maximizing the throughput. While we only present a part of simulation results, where the network topology depicted in Fig. 4 is used, in this paper due to the space limitation, the similar results have been obtained through all other simulations.

4.2 Validate the optimal node selected as the gateway

In this simulation, we take an example (see Fig. 4) to estimate the throughput. Through analytical analysis, we know that the optimal node can be selected as the gateway to guarantee the maximum network throughput among all nodes in the network. Herein, we would like to validate consistency with our analysis by running the simulation experiments. Each node has the different traffic to transmit to the gateway as shown in Fig. 4. Based on our gateway selection method, we can estimate that node v_2 has the minimum traffic in the bottleneck collision domain (which is equal to $87D$) among the whole nodes in the network, which is selected as the gateway in this model. Fig. 5 shows the change of the throughput when each node is served as the gateway respectively. From this figure, we can clearly see that the simulated result is consistent with the analyzed result that it has the maximum throughput when

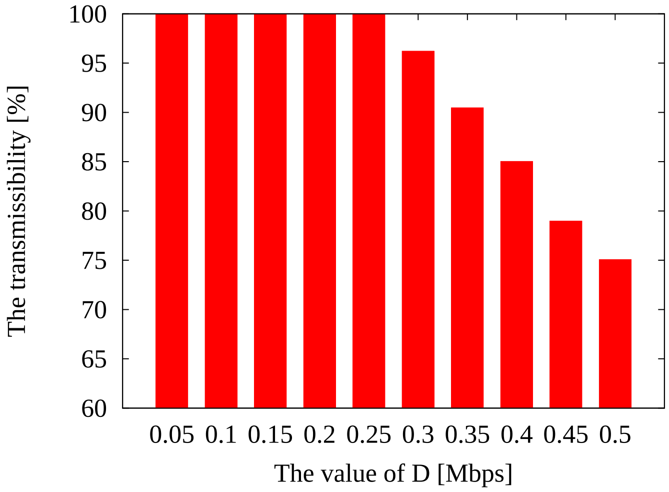

Fig. 6 Illustration of the transmissibility.

node v_2 is served as the gateway. It demonstrates that our method is effective and correct.

4.3 Adjust the traffic load for throughput optimization

In this section, we run the simulation to optimize the throughput by adjusting the traffic load for each node. Note that, in order to eliminate the congestion, we should control the traffic for each node in terms of the upper bound throughput. This simulation experiment estimates the impact of the throughput on the increasing traffic demand. In Fig. 6, the transmissibility is defined as the proportion of the successfully transmitted traffic to the total traffic demand. For example, when the transmissibility is equal to 100%, it means that each node can transmit all its traffic successfully without traffic congestion. From this figure, we can see that, when the traffic demand D equals to 0.3Mbps (according to Fig. 4, $D_{max} = 0.3$Mbps), the transmissibilility starts to decrease gradually. The transmissibility is significantly degrade with D increasing. We can maximize throughput without causing traffic congestions by regulating traffic load from each node according to the upper bound throughput derived from our algorithm.

5 Related Works

In this section, we briefly introduce the various methodologies in the literature for estimating the network capacity. Over the recent years, researchers have been dedicated to the problem of the throughput capacity for wireless mesh networks. They have provided many techniques to analyze the capacity of wireless mesh networks, like [9], [10], [16], [17], [18], [19], etc.

P. Gupta *et al.* [18] proposed a solution to investigate the lower and upper bounds of network capacity under a protocol model of non-interference. The result has been demonstrated that splitting the channel into several subchannels does not affect the bounds of network capacity. It also showed an important result that, as the node density increases, the throughput capacity will significantly decrease. However, this work analyzed all paths follow straight lines and did not consider the impact of routing-related.

J. Jun *et al.* [9] presented a method to obtain the exact upper bound throughput of a WMN. It considered a theoretical model to determine the nominal capacity of WMNs, which contains one gateway in the network that each node has an infinite amount of data to send to the gateway. According to the key technique, bottleneck collision domain, which is defined as the geographical area of the network that bounds from above the amount of data that can be transmitted in the network, it provided the conclusion that the throughput of each node decreases as $O(1/n)$, where n is the total number of nodes in the network. The concept of collision domain is used in our method.

B. Aoun *et al.* [17] focused on the max-min fair capacity of wireless mesh networks. They proposed an algorithm for max-min capacity calculation in term of collision domains. Nevertheless, they took into account the scenario of only single channel for WMNs, without multi-radio multi-channel network.

N. Akhtar *et al.* [10] illustrated an analytical grid-based framework for analyzing the capacity of multi-radio multi-channel wireless mesh networks. It evaluated the influence of various network design parameters (e.g., grid size, the number of aggregator nodes, single and multiple paths, and routing approach) on the network capacity, especially the maximum throughput available for each mesh router can be obtained for various scenarios. It also analyzed the nominal capacity based on the same traffic for each node. However, there is a possible situation that each mesh router is distributed by different traffics. We would like to take into account the scenario of the uneven traffic distribution and guarantee the maximum throughput capacity in the network.

6 Conclusion

In this paper, we proposed a novel gateway selection technique to optimize the throughput for wireless mesh networks in disaster areas. The contributions of our work including: we presented a novel gateway selection algorithm to decide the optimal mesh router as the gateway in the wireless mesh network that can effectively maximize the network throughput capacity and reduce the computing complexity; we assigned the traffic for the mesh routers based on the upper bound throughput to eliminate the traffic congestion. The simulation results demonstrated that our proposed gateway selection method has high accuracy and efficiency to optimize the network throughput.

References

1. I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: a survey,” *Comput. Netw. ISDN Syst.*, vol. 47, no. 4, pp. 445-487, 2005.
2. P. H. Pathak and R. Dutta, “A survey of network design problems and joint design approaches in wireless mesh networks,” *IEEE Communications surveys & tutorials*, vol. 13, no. 3, Third Quarter 2011.
3. D. Benyamina, A. Hafid, and M. Gendreau, “Wireless mesh networks design - A survey,” *IEEE Communications surveys & tutorials*, vol. PP, no. 99, 2011.
4. R. Bhatia and L. Li, “Throughput optimization of wireless mesh networks with mimo links,” *26th IEEE International Conference on Computer Communications. INFOCOM 2007.* Anchorage, Alaska, USA, pp. 2326-2330, May 2007.
5. G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, March 2000.
6. P. C. Ng and S. C. Liew, “Throughput analysis of IEEE 802.11 multi-hop ad hoc networks,” *IEEE/ACM Transactions on networking*, vol. 15, no. 2, Apr. 2007.
7. M. Fouda, H. Nishiyama, and N. Kato, “A Novel Heuristic-based Traffic Distribution Method for Disaster Zone Wireless Mesh Networks,” *1st IEEE International Conference on Communications in China (ICCC 2012)*, Beijing, China, Aug. 2012.
8. W. Liu, H. Nishiyama, N. Kato, Y. Shimizu, and T. Kumagai, “A Novel Gateway Selection Method to Maximize the System Throughput of Wireless Mesh Network Deployed in Disaster Areas,” *23rd IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2012)*, Sydney, Australia, Sep. 2012.
9. J. Jun and M. Sichitiu, “The nominal capacity of wireless mesh networks,” *IEEE Wireless Communications.*, vol. 10, no. 5, pp. 8-14, Oct. 2003.
10. N. Akhtar and K. Moessner, “On the nominal capacity of multi-radio multi-channel wireless mesh networks,” *Computer Communications*, vol. 31, no. 8, May 2008.
11. J. Jun, P. Peddabachagari, and M. L. Sichitiu, “Theoretical maximum throughput of IEEE 802.11 and its applications,” in *Proc. Second IEEE International Symposium on Network Computing and Applications. NCA 2003.*, Cambridge, MA, pp. 249-256, Apr. 2003.
12. Wireless LAN medium access control (MAC) and physical layer (PHY) specification, IEEE Standard 802.11, June 1999.
13. Wireless LAN medium access control (MAC) and physical layer (PHY) specification: High-speed physical layer extension in the 2.4 GHz band, IEEE Standard 802.11, Sept. 1999.
14. Wireless LAN medium access control (MAC) and physical layer (PHY) specification: High-speed physical layer extension in the 5 GHz band, IEEE Standard 802.11, Sept. 1999.
15. Scalable Network Technologies: Qualnet, http://www.scalable-neworks.com
16. V. Bhandari and N. Vaidya, “Connectivity and capacity of multi-channel wireless networks with channel switching constraints,” *26th IEEE International Conference on Computer Communications. INFOCOM 2007.* Anchorage, Alaska, USA, pp. 785-793, May 2007.
17. B. Aoun and R. Boutaba, “Max-min fair capacity of wireless mesh networks,” in *Proc. of the 3rd IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, Oct. 2006.
18. P. Gupta and P. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388-404, Mar. 2000.
19. J. Li, C. Blake, D. S. I. D. Couto, H. I. Lee, and R. Morris, “Capacity of Ad Hoc Wireless Networks,” in *Proc. of 7th ACM International Conference on Mobile Computing and Networking (MobiCom ’01)*, Rome, Italy, July 2001.