A Novel Gateway Selection Method to Maximize the System Throughput of Wireless Mesh Network Deployed in Disaster Areas

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A Novel Gateway Selection Method to Maximize the System Throughput of Wireless Mesh Network Deployed in Disaster Areas

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Abstract*—Since Wireless Mesh Networks (WMNs) can be easily deployed without wirelines among wireless mesh routers, they allow us to quickly recover network access services in disaster areas even if the existing network infrastructures have been enormously destroyed by terrible earthquake, tsunami, and so on. However, the performance of wireless mesh networks is largely affected by many factors, e.g., wireless mesh routers' locations, channel assignment, transmission scheduling, etc. In particular, the method of selecting gateways which has a connection to external networks significantly impacts on the network performance when the topology and routing have been fixed in the wireless mesh network. In this paper, we suppose a wireless mesh network which consists of wireless mesh routers and a base station directly connected to external networks. The base station is located at the center of the wireless mesh network chooses a certain number of wireless mesh routers as gateways, and establishes a connection with each of them. Our goal is to easily and quickly find the candidate gateways that maximize the system throughput without solving a complex optimization problem which includes a large number of parameters and involves heavy computation load. The performance of the proposed scheme is evaluated by numerical analysis, and demonstrated through computer simulations. The results show that our proposed scheme can determine the appropriate candidate gateway with high accuracy when there is a certain variance in the amount of traffic generated by users at each wireless mesh router.

I. Introduction

Wireless mesh networks (WMNs) are a quickly emerging technology for last mile broadband Internet access in recent years. In WMNs, nodes consist of wireless mesh routers and mesh clients. Each node acts not only as an end user but also as a router, forwarding packets on behalf of other nodes whose destinations are not within its direct wireless transmission range.

Nowadays, WMNs have received increasing attention due to their various attractive advantages [1], [2], [3], like low up-front cost, easy network deployment, stable topology, robustness, reliable coverage, and so forth. WMNs also inherit the useful characteristics from the ad hoc network paradigm, with the capability of self-forming, self-healing, and self-organization. In particular, these characteristics are very suitable for the disaster recovery application. We know that reliable and efficient communication is absolutely crucial for the communications in the disaster area. For example, recent events such as the 3-11 earthquake in Japan, which destroyed a great number of wireless base stations, unfortunately demonstrated that the remaining functional parts of the network were unable to provide adequate services. WMNs can be helpful to first respond communications after the disaster occurs. Fig. 1 shows an example of WMN infrastructure designed by considering an actual disaster area. Here, we divided the network into three hierarchies. The top hierarchy is deploying a base station located at the center of the wireless mesh network to take charge of the whole area, choosing a certain number of wireless mesh routers as gateways, and establishing a connection with each of them by point-to-point with 25GHz band. Note that the WMN is comprised of a set of wireless mesh routers and mesh clients (e.g., mobile phones, laptops, and PocketPCs). The middle hierarchy consists of wireless mesh routers that make up the network backbone with one or more of these nodes directly connected to the base station as the gateway, in which the currently widely used standard, 802.11a with high frequency band (5 GHz), is used in the network backbone. The bottom consists of mesh clients that are deployed at the edge to communicate with the mesh routers by using 802.11b with 2.4 GHz.

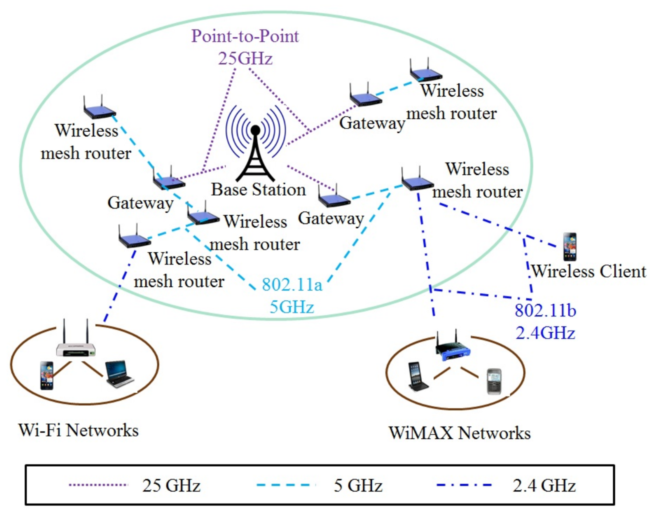

Fig. 1. An example of a wireless mesh network infrastructure.

Moreover, to recover communications in a disaster area, we deploy a number of wireless mesh routers to construct the backbone network and select some of them as the gateways to directly link the base station to connect to the Internet (see Fig. 1). However, choosing different mesh routers as the gateway will bring different network performance. Throughput is one of the major criteria to evaluate network performance [4], [5], [6]. In a certain area, how to choose a mesh router as the gateway to provide maximum available system throughput has been a key issue in recent years. Therefore, in this paper, we would like to propose a new method to select a mesh router as the gateway in the disaster area to maintain high system throughput of the deployed network.

The remainder of this paper is organized as follows. In section II, we give a brief overview of related works on throughput analysis techniques in WMNs. Section III presents our proposed method to select the optimal node from the candidates as the gateway, in order to improve the system throughput in the wireless mesh network. We devote section IV to the performance evaluation of our method. Finally, we conclude the paper in section V.

II. Related Work

Recently, researchers have been concentrating their attention on the issue of analyzing WMNs throughput capacity. There are many techniques to analyze the capacity of wireless mesh networks [7], [8], [9], [10], [11], [12]. In this section, we briefly introduce the existing classic approaches for investigating the network capacity.

P. Gupta *et al.* [12] present a solution to estimate the lower and upper bounds of network capacity under a protocol model of noninterference. The result showed that splitting the channel into several subchannels does not affect the results of bounds of network capacity. It also provided an important result that the throughput capacity is sharply decreasing with node density increasing. However, this work analyzed all paths follow straight lines and did not consider routing-related effects.

J. Jun *et al.* [8] proposed 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. By using this method, we can calculate the maximum available system throughput and evaluate the quality of service and capacity of the network. However, this method only considered the single channel in WMNs, not multi-radio multi-channel.

N. Akhtar *et al.* [9] proposed an analytical grid-based framework for estimating the capacity of multi-radio multi-channel wireless mesh networks. In this work, it is to study the impact of various network design parameters (e.g., grid size, the number of aggregator nodes, single and multiple paths, and routing approach) on WMNs capacity, on the basis of the concept of collision domain that is used to calculate an upper bound on the capacity available to the nodes that generate traffic towards the gateway to connect to the Internet, especially the maximum throughput available for each mesh router can be obtained for various scenarios. In this method, it analyzed the nominal capacity based on the same traffic for each node. However, owing to the possible situation that not all nodes have an equal traffic load, the traffic of each mesh router is distributed to different classes, some heavy and some light. For example, a number of nodes can receive several times the traffic load than others, which G is assigned as the unit traffic load, and kG is denoted the different traffic loads for each mesh router. We would like to consider the uneven traffic situation and insure the maximum system throughput in the network.

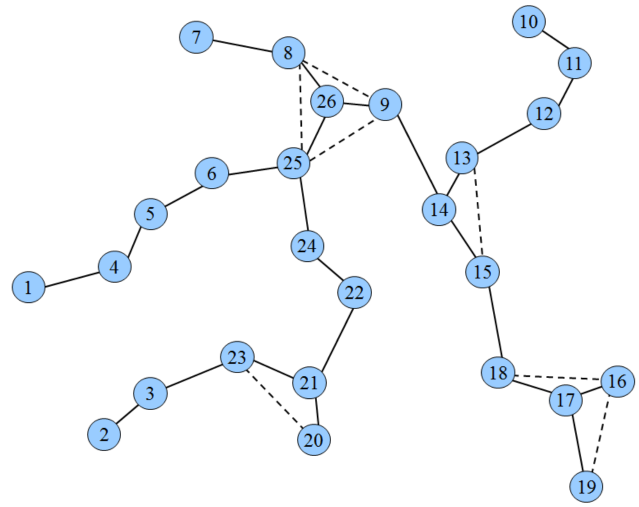

Fig. 2. A topology of wireless mesh network by MST.

III. A Gateway Selection Method

In this section, we propose a novel method to choose the gateway for deploying a WMN for disaster recovery, in achieving the maximum system throughput.

According to the infrastructure described in Fig. 1, a realistic application has been deployed in Japan. The base station can select a number of wireless mesh routers as gateways, and establish a connection with each of them. Particularly, due to the base station supports one channel, in this paper, we assume that mesh routers connect to each other by the single channel. Moreover, note that we consider only one gateway in a certain area. If there are multi-gateways, the problem can be solved by separating the nodes related to one gateway from nodes associated to other gateways, which is beyond the research scope of this paper. Here, we design a network topology to analyze the system throughput. We randomly deploy the

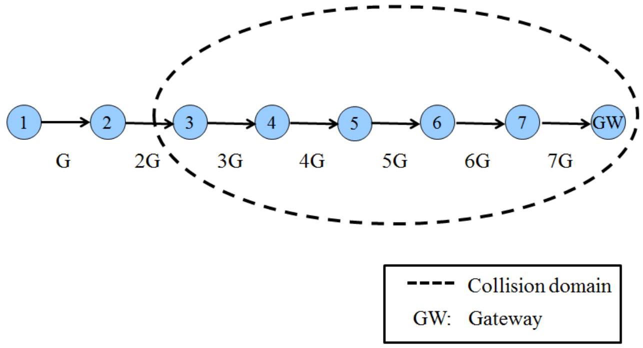

Fig. 3. A chain of 7 nodes generating and relaying packet to the gateway.

wireless mesh router nodes within a certain area, and they contact with adjacent nodes when the distance between two of them is less than the transmission range. Note that, in this topology, we do not consider routing attacks when set up the routing path, interested readers can reference the literatures [13], [14]. We utilize the Minimum Spanning Tree (MST) algorithm to delete the redundant paths (the dashed line in Fig. 2) and maintain the unique routing path for our network topology. The constructed topology model is shown as Fig. 2.

A. Theoretical maximum throughput

To track the issue of calculating available system throughput, there are two key factors to affect the result. One is the theoretical maximum throughput T_{max} in MAC layer [15]. Note that, to calculate the theoretical maximum throughput of 802.11 networks, we should consider a number of parameters, such as physical layer and MAC layer variations, packet size, and basic data rates, etc. We can get the value of T_{max} by utilizing Eq. 1,

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

where MAC Service Data Unit (MSDU) is defined as a packet pushed from the higher layer down to the MAC layer, and T_{delay} is the consumed time for transmitting per MSDU packet, including the components like 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. To estimate the result, it is necessary to convert all of the components into a common unit time. The values of these delay components can be obtained from the IEEE standard [16]. As a consequence, we can calculate the exact result of theoretical maximum throughput in MAC layer.

B. Bottleneck collision domain

After obtaining the theoretical maximum throughput T_{max}, we then determine another key factor, the bottleneck collision domain, which is the collision domain that has to forward the most traffic in the network, to analyze the throughput of the network. Here, the collision domain is defined as a set of wireless links with the shared nature that connects mesh router nodes. Note that using a common channel implies that only one node is able to successfully transmit in the collision domain, while all other nodes in the immediate vicinity cannot transmit at the same time. As shown in Fig. 3, we assume a simple chain topology of seven nodes generating and relaying packet to the gateway. Here, each node transmits the same traffic G to the gateway and can only forward packets from its immediate neighboring node. The interference range is twice over the transmission range. From Fig. 3, it is clearly seen that, since each link is constrained to transmit only when others within its interference range is inactive, the collision domain of the link 5-6 consists of the links (7-GW, 6-7, 5-6, 4-5, 3-4). Note that each collision domain has to be able to transmit the total traffics of its links. Then the collision domain of link 5-6 has to transmit $25G$ ($3G + 4G + 5G + 6G + 7G$); in the same way, the collision domain of link 2-3 is equal to $10G$ ($1G + 2G + 3G + 4G$). Based on the analysis, we know that the bottleneck collision domain is link 5-6 in this chain model. Therefore, the available throughput can be reached the upper bound G_{max}, when it is equal to the theoretical maximum throughput in MAC layer T_{max} divided by the Bottleneck Collision Domain (BCD) [8] as shown in Eq. 2.

$$G_{max} = \frac{T_{max}}{\text{BCD}}. \tag{2}$$

Moreover, we refer to an extension literature [9] to analyze the upper bound on the throughput in multi-radio multi-channel network, which can be calculated by

$$G_{max} = \frac{T_{max}}{\sum_{l \in C_B} \sum_{a=1}^{K} \lambda_{a,l}}, \tag{3}$$

where l is a link in the bottleneck collision domain C_B, a denotes one of K original sending nodes, $\lambda_{a,l}$ means the fraction of traffic originating from node a traversing link l. In Eq. 3, we know that the crucial condition is to determine the bottleneck collision domain of each link, which is directly affected by the interference range of wireless nodes and the routing path of the network topology.

Based on the above presented approaches, we consider the case when the traffic load for each node is differently distributed in the following, and propose an effective method to locate the optimum node as the gateway, improving the system throughput under uneven traffic distributed situation.

C. Selecting a wireless mesh router as the gateway

In the disaster area, when we prepare to deploy a wireless mesh network to recover communications, it is inevitable the situation that a number of mesh router nodes take on heavy loads and others are light. Under this case, we cannot simply deploy the gateway in the center of the network, since different nodes as the gateway will bring different system throughput. Therefore, we need to select an optimal node as the gateway to ensure the maximum throughput in the network. Furthermore, we know that the throughput depends on the theoretical maximum throughput T_{max} and the bottleneck collision domain. T_{max} can be exactly calculated as a constant value by the given 802.11 protocol [15]. In other words, the bottleneck collision domain is the key factor to affect the optimal throughput in the network. As a consequence, our work is changed into choosing the mesh router node as the gateway who has the smallest bottleneck collision domain.

As we known, the bottleneck collision domain relates to the routing path. Different routing paths will lead to various collision domain. Therefore, we first set up an analytical model to design the network topology with unique routing path as shown in Fig. 2. Based on the aforementioned approaches and the constructed model, we can calculate the throughput for every node assigned as the gateway, and then select the node that has the maximum system throughput to be as the gateway. This is the simplest way to choose the gateway. However, since it is impossible to traverse all of the nodes in the network and the efficiency is very low, that method is not suited to the realistic applications. As a consequence, we propose a new method to select the gateway so as to reduce the range of candidate nodes and improve the efficiency as follows:

Step 1: In our method, we first focus on the nodes who have the heavy loads. This is because each mesh router receives different traffic loads and different traffic loads generate different values of the bottleneck collision domain. These nodes are vital to influence on the bottleneck collision domain. Therefore, from all of the mesh routers, we choose the number of top N nodes with heavy traffics as the basic nodes, which account for the vast majority of traffic loads in the network.

Step 2: Then, we concentrate on narrowing down the range of the candidate nodes by utilizing the selected top N nodes. We assign the nodes that are on the routing path between two of N as the candidate gateways. In particular, when the top N selected nodes are closely linked and no other wireless mesh routers between them, we assign these selected nodes as the candidates. Because the selected nodes occupy a large proportion of total traffic loads, if the gateway is out of the scope of our determined, the heavy traffic will transmit through a common link, increasing the probability of network congestion and the bottleneck collision domain. Note that, by using this method, we can effectively reduce the number of candidate nodes so as to enhance the efficiency.

Step 3: Furthermore, according to the analytical calculation method presented in Section III-A and Section III-B, we can estimate the system throughput on basis of each candidate nodes regarded as the gateway.

Step 4: Finally, through comparing the results of each candidate nodes, we can determine the given node as the gateway, which enable the network to have the maximum throughput.

The flow chart of our gateway selection algorithm is shown in Fig. 4. For example, as shown in Fig. 2, if the nodes 5, 7, and 20 have the highest traffic loads and account for a great proportion of all nodes in the network, we choose them as the basic nodes. Then, we can determine the nodes 6, 8, 21, 22, 24, 25, and 26 as the gateway candidates, which are on the routing path between the basic nodes. Note that nodes transmission in the network is based on the MST routing selection algorithm. We are able to get the theoretical maximum throughput equal to 26.8Mbps for 802.11a with the basic data rate 54Mbps [15] and estimate the bottleneck collision domain for each candidates. Finally, according to the numerical results, we are able to select the optimum candidate node as the gateway in this area, which has the smallest bottleneck collision domain.

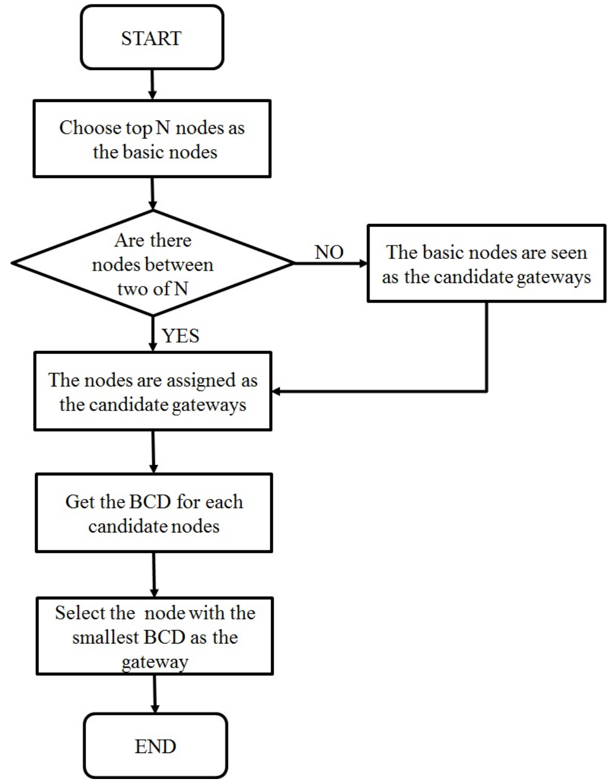

Fig. 4. The flow chart of gateway selection algorithm.

IV. Performance Evaluation

In this section, we evaluate the performance of our method conducted in the network simulator, Qualnet 5.1 [17]. To demonstrate the maximum available throughput and capacity obtained by using our proposed method, we design the experiments to measure the system throughput in comparison with those of numerical results. In addition, we also estimate the accuracy of selecting the optimum wireless mesh router as the gateway by using the new method.

A. Simulation setup

We consider a disaster area constructed by a wireless mesh network, where every mesh router has different traffic loads. We simulate this WMN environment within 500m by 500m terrain using 802.11a with the basic data rate 54 Mbps. We set the packet size to 1500 bytes, and then the theoretical

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Simulator	Qualnet 5.1
Mobility model	Stationary
Terrain dimensions	500m x 500m
Protocol	802.11a
Basic data rate	54 Mbps
Packet size	1500 Bytes
T_{max}	26.8 Mbps
Transmission range	100m

TABLE II
TRAFFIC DISTRIBUTION FOR DIFFERENT SCENARIOS

Node ID	Scenario 1 Traffic [G]	Scenario 2 Traffic [G]	Node ID	Scenario 1 Traffic [G]	Scenario 2 Traffic [G]
1	9	3	14	30	29
2	5	21	15	19	27
3	18	5	16	3	27
4	20	2	17	8	27
5	25	12	18	14	31
6	37	37	19	7	33
7	39	39	20	2	12
8	34	21	21	11	7
9	15	29	22	21	28
10	14	21	23	6	29
11	7	28	24	36	36
12	12	33	25	13	28
13	6	22	26	20	14

maximum throughput T_{max} can be calculated as 26.8 Mbps [15]. We assume that all nodes are stationary in the network, and all of the traffics are transmitted to the gateway. The transmission range of each node is set to 100 meters and the interference range is twice over the transmission range. The specific parameter settings are listed in Table I.

B. Comparing the throughput with different nodes as the gateway

To select the optimal node as the gateway, we first decide the candidate nodes by using our proposed method. The analytical topology is deployed as shown in Fig. 2, specifying the shortest routing path for the network topology on the basis of the MST algorithm, since different routing path is able to affect the bottleneck collision domain, and the unique routing path is helpful to evaluate the performance of our new method. The traffic loads are randomly distributed to every node as scenario 1 shown in Table II. According to the distributed traffics in scenario 1, we can see that the top 3 nodes 6, 7, and 24 with the highest traffic loads, are selected as the basic nodes. We then can lock the candidate nodes (8, 25, and 26) that are on the routing path between the basic nodes 6, 7, and 24. By utilizing aforementioned capacity evaluated approach, we can analyze the bottleneck collision domain, and then exactly calculate the maximum available system throughput, determining which candidate node is assigned as the gateway. Fig. 5 shows us the comparison of the numerical result and simulated result. From this figure, we can clearly observe that the results of the system throughput by the simulation are consistent with the numerical results. Additionally, we can

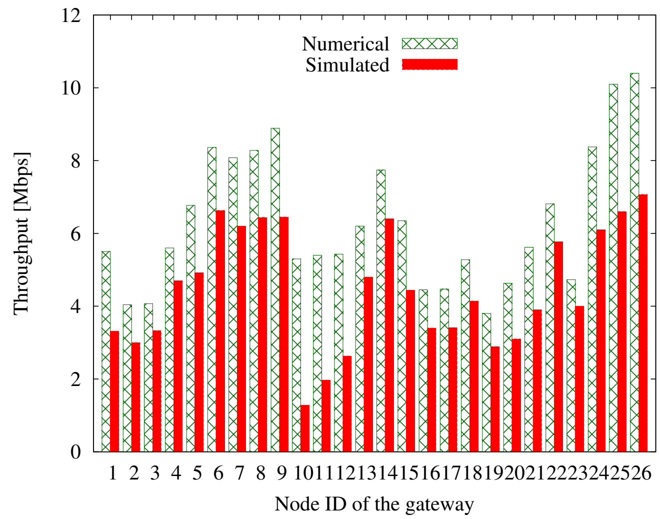

Fig. 5. Comparison of the system throughput with different nodes as the gateway.

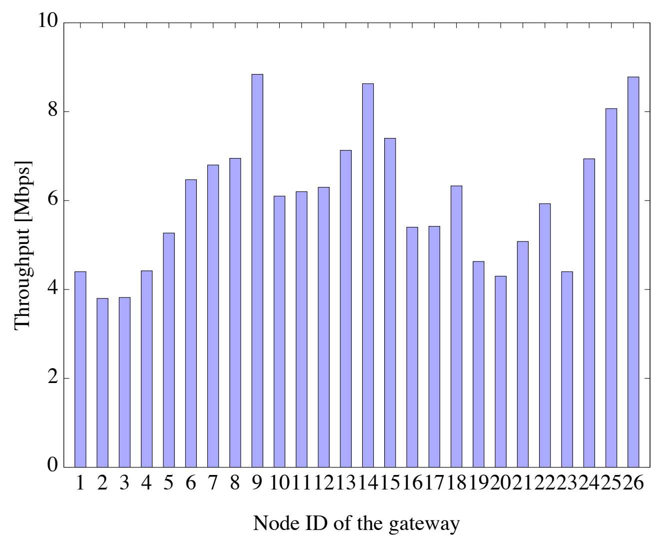

Fig. 6. The system throughput with respect to different nodes as the gateway.

also find that, when node 26 is regarded as the gateway, the network has the largest throughput among all nodes that will be selected as the gateway in the network. In particular, note that node 26 is within our candidate range.

C. Accuracy of selecting the candidate nodes

There is a major factor that affects the accuracy of our proposed method. For example, as scenario 2 shown in Table II, we select top 3 nodes 6, 7, and 24 as the basic nodes. After that, we can determine the candidates as nodes 8, 25, and 26. From Fig. 6, we can find that the system throughput of candidates 8, 25, and 26 (6.95 Mbps, 8.07 Mbps, and 8.78 Mbps) are all smaller than node 9 (8.84 Mbps). In other words, the optimal gateway is out of our determined candidate range. This is because the different distributed traffic loads affect the bottleneck collision domain, namely, influence the system

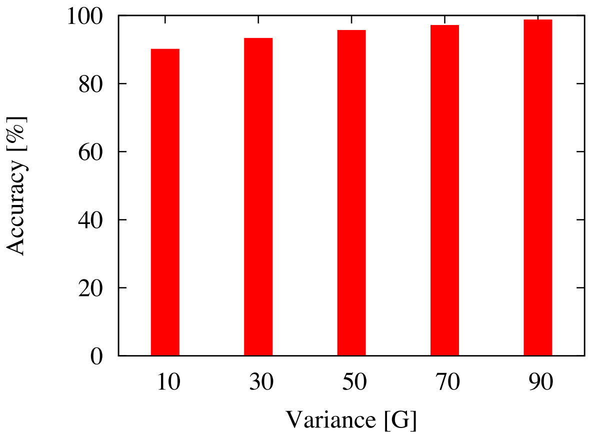

Fig. 7. Impact of the variance on the accuracy.

throughput, and the sum of traffic loads of the basic nodes does not account for a large proportion of total amount.

However, although the optimal node is out of the our candidate range, note that the system throughput of our candidate node 26 (8.78 Mbps) is very close to the maximum throughput (8.84 Mbps). Therefore, we would like to estimate the relationship between the accuracy and the variance, where the accuracy denotes the ratio of the largest system throughput of our candidate node to the maximum throughput in the network, and the variance means the range of distributed traffic loads to each node. Here, we design the experiment that gradually increase the value of the variance to observe the impact on the accuracy by using our proposed method. We select top 3 nodes as the basic nodes. With the value of the variance increasing, the sum of traffic loads from the basic nodes occupies more proportion. As shown in Fig. 7, we can clearly see that, the accuracy of our scheme is improving as the variance increases. As a consequence, the results demonstrate that our proposed method can be effective and efficient when the traffic loads of each nodes are different distributed in the network and the basic nodes account for a large proportion of the total traffics.

V. Conclusion

In this paper, we have addressed a major issue, which is quickly selecting a wireless mesh router as the gateway in the wireless mesh network, in order to provide the maximum system throughput. In contrast to existing algorithms, we consider the realistic environment for disaster area, in which each mesh router has different traffic loads. We have proposed a novel method that easily assigns a few nodes as candidate gateways that are on the routing path between the selected basic nodes. In doing so, we can calculate the system throughput for each candidate node and then select the node with maximizing the system throughput as the gateway, without the need for solving a complex optimization problem which includes a large number of parameters and involves heavy computation load. In addition, the performance of the proposed method is evaluated by numerical analysis, and demonstrated through computer simulations. The extensive results have demonstrated that our proposed method can be effective and efficient in determining the appropriate candidate of the gateway with high accuracy when there is a certain variance in the amount of traffic generated by users at each wireless mesh router, reducing the computing complexity, and maximizing the system throughput of the wireless mesh network. Therefore, our method would be very useful for quickly deploying wireless mesh networks for disaster recovery.

Acknowledgement

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