Extending the Protocol Interference Model Considering SINR for Wireless Mesh Networks

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***Abstract*—Radio interference should be taken into account to assign time slots to links in time division multiple access (TDMA)-based wireless mesh networks. In many graph theory-based time slot assignment algorithms, the protocol interference model is widely used to obtain radio interference information, although this model is considered to be inaccurate when compared with actual radio interference. On the other hand, the signal-to-interference-plus-noise-ratio model (SINR model) is a well-known and accurate model of radio interference. However, the SINR model requires time slot information to obtain radio interference relationship, and thus it is difficult to apply the SINR model to graph theory-based time slot assignment algorithms. In this paper, we extend the protocol interference model to represent radio interference more accurately for wireless mesh networks. To do this, we adjust the interference ratio parameter of the protocol interference model by considering SINR. We propose three methods for adjusting this parameter. Through simulation, it is shown that higher accuracy of the protocol interference model can be achieved by adjusting the interference ratio parameter for each node.**

***Keywords*-wireless mesh networks, protocol interference model, signal-to-plus-noise-ratio model, time slot assignment.**

I. INTRODUCTION

Wireless mesh networks have attracted a great deal of attention for providing wireless broadband access because of their expandability and cost efficiency [1]. Wireless mesh networks consist of a gateway node which is connected to a wired network and mesh nodes which relay the messages between the gateway node and client terminals as shown in Fig. 1. A mesh node is connected with another node through a wireless link when they are within transmission range of each other. A mesh node provides wireless broadband access service to client terminals within its service area.

In wireless networks, when closely located links are simultaneously used, a receiver node cannot correctly receive radio signals from the corresponding sender node due to radio interference. That is why it is necessary to avoid radio interference in wireless networks. In the time division multiple access (TDMA) protocol, time is divided into frames, each of which consists of time slots of constant duration. Different time slots are then assigned to links that interfere with each other. The performance of the wireless mesh networks highly dependent on the time slot assignment algorithms, and graph theory-based time slot assignment algorithms for wireless mesh networks have been studied [2, 3, 4] since time slot assignment algorithms can be regarded as the graph coloring in graph theory.

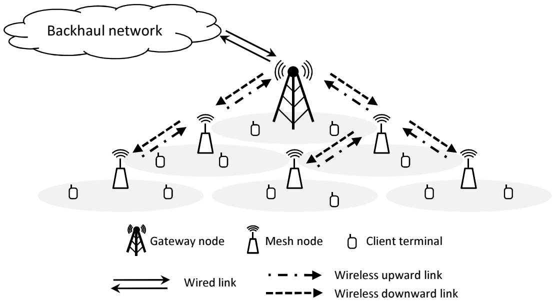


Figure 1. Wireless mesh network

Graph theory-based time slot assignment algorithms require information on the interference relationships among links before assigning time slots to links. In these algorithms, the *protocol interference model* (a.k.a. unified disk graph model) [5, 6] has been widely used to obtain radio interference information. In the protocol interference model, a radio interference range is defined as a circle centered on a sender node. Since the interference relationships among links are defined according to the location of nodes, the protocol interference model can be easily used in theoretical analysis. However, the protocol interference model is not accurate in comparison with physical radio interference [6]. For example, closely located links can be used simultaneously when each receiver node can receive signals of sufficient strength from the corresponding sender node, even if the protocol interference model indicates that the links interfere with each other [7]. In addition, there is a situation in which a receiver node cannot correctly receive radio signals from the corresponding sender node when many links are simultaneously used and interfere with the receiver node, even if there are no interference relationships among the links in the protocol interference model.

On the other hand, the *signal-to-interference-plus-noise ratio (SINR) model* [6, 7] is known for accurate radio interference representation. In the SINR model, when the signal-to-interference-plus-noise ratio of a link is beyond a threshold value, the receiver node of the link can successfully receive the radio signal from the sender node of the link. The SINR model can handle features of wireless radio propagation such as Rayleigh fading, shadowing effects and capture effects[8]. However, to obtain interference relationships among links, the SINR model requires information not only on the location of nodes, but also on sender nodes which simultaneously emit radio signals. Therefore, it is difficult to apply the SINR model to the graph theory-based time slot assignment algorithms.

To apply the graph theory-based time slot assignment algorithms to actual wireless mesh networks, accurate information on interference relationships is needed in order to avoid interference among links and to assign time slots to links efficiently. In other words, accurate radio interference models are needed that can be applied in graph theory-based time slot assignment algorithms. For this purpose, in this paper we extend the protocol interference model considering SINR. This is accomplished by adjusting the interference ratio parameter of the protocol interference model. The overview of our proposal is as follows. For a wireless mesh network, interference relationships are at first determined based on the protocol interference model. Then, time slots are assigned for all links based on the information on the interference relationships. These steps are repeated by adjusting the interference ratio parameter until all links satisfy certain SINR criteria. We propose three heuristic methods for adjusting the parameter. The accuracy and effect of our proposed radio interference models are evaluated through simulation experiments.

The rest of this paper is organized as follows. In Section II, we introduce some related studies. In Section III, we describe the network model and radio interference models. Then in Section IV, we propose three methods for adjusting the interference ratio parameter of the protocol interference model, considering the SINR; these methods are evaluated through simulation in Section V. Finally, we conclude this paper and discuss future work in Section VI.

II. RELATED WORK

To assign time slots to links in TDMA-based wireless networks, information on interference relationships among links is needed. There are a variety of radio interference models for wireless networks, and these radio interference models have been compared in previous studies [6, 9, 10].

Maheshwari et al. have investigated the accuracy of radio interference models in IEEE 802.15.4-based wireless sensor networks [9]. They conducted experiments using 20 TelosB commercial sensor nodes, and evaluated the accuracy of the protocol interference model, the SINR model, the hop-based interference model, the link quality-based interference model and the range-based interference model. As a result, they found that the SINR model is the most accurate among the radio interference models when compared with actual radio interference. Furthermore, they evaluated the throughput of the wireless sensor network using a time slot assignment algorithm based on each radio interference model. For the SINR model, the authors used one-shot scheduling [11]. Through experimentation, they demonstrated that the time slot assignment based on SINR model achieves the highest throughput.

Zhu and Lu have compared the physical radio interference model and the hop-based interference model, which is used in IEEE 802.16 wireless mesh networks [10]. Through simulation evaluations using a QualNet simulator, it was shown that about 7% of links cannot be used due to radio interference when we assume that there are interference relationships among links within 3-hop links in the hop-based interference model.

Shi et al. have compared the protocol interference model and the SINR model for multi-hop multi-channel wireless networks [6]. They first show that blind use of the protocol interference model is not adequate. They then show that the link capacity of wireless networks based on the protocol interference model can be close to that based on the SINR model by using appropriate parameter settings for the protocol interference model.

In the present study, we extend the protocol interference model in order to use it in graph theory-based time slot assignment algorithms for wireless mesh networks. Taking the SINR as an accurate measure of the actual radio interference, we propose methods for adjusting the interference ratio parameter of the protocol interference model.

III. MODELS

In this section, we explain the wireless mesh network model and the time slot assignment algorithm which are used in this paper. We then introduce the protocol interference model and SINR model.

A. Wireless Mesh Network

In this paper, we consider the same wireless mesh network that is used in [3]. We assume that there is a set of n mesh nodes $\mathcal{V}^c = \{v_1, v_2, \ldots, v_n\}$ deployed in a plane. We consider the directed communication graph $\mathcal{G}^c = (\mathcal{V}^c, \mathcal{E}^c)$ which indicates the communication relationship in each node. $\mathcal{E}^c$ is the set of directed communication links $l_{i,j}$, representing a link directed from mesh node $v_i \in \mathcal{V}^c$ to mesh node $v_j \in \mathcal{V}^c$. The existence of directed communication link $l_{i,j}$ in the directed communication graph $\mathcal{G}^c$ is determined according to the radio interference model. We assume one of the mesh nodes is the gateway node that is connected to a wired network. Without loss of generality, let mesh node v_1 be the gateway node.

There are two types of communication, namely, upward communication and downward communication. In upward communication, data is transferred from mesh nodes toward the gateway node. Conversely, data is transferred from the gateway node toward mesh nodes in downward communication. Communication between the gateway node and mesh nodes is achieved through intermediate mesh nodes in a multi-hop fashion. The communication path is determined by a routing algorithm. In this paper, we consider a tree-based routing algorithm which constructs the transmission graph $\mathcal{G}^t = (\mathcal{V}^t, \mathcal{E}^t)$ as a tree graph. Here, $\mathcal{G}^t \subset \mathcal{G}^c$, $\mathcal{V}^t = \mathcal{V}^c$ and $\mathcal{E}^t \subset \mathcal{E}^c$. In the transmission graph, root is the gateway node and each node is connected to the gateway node through minimum hop and minimum distance links. We call the link $l_{i,j} \in \mathcal{E}^t$ in $\mathcal{G}^t$ a transmission link. In addition, a link that is on the path directed toward the gateway node is called an upward link, and a link that is on the path directed away from the gateway node is called a downward link.

B. Time Slot Assignment

In this paper, TDMA is adopted as the MAC protocol of the wireless mesh networks. In TDMA, time is divided into time slots $\mathcal{T} = \{t_1, t_2, \ldots, t_m\}$, and different time slots are assigned to the links which have an interference relationship. In this paper, the total number of time slots m is called the frame length. The interference relationships of the links are determined by the radio interference model. For the time slot assignment algorithm at the transmission link $l_{i,j} \in \mathcal{E}^t$, we adopt the greedy algorithm that is used in [2, 3]. In this time slot assignment algorithm, the order of time slot assignment for each transmission link is first determined, and then time slots are assigned to the transmission links in a greedy manner. The frame length m becomes the number of time slots, depending on the deployment of mesh nodes and the interference relationship among transmission links.

C. Radio Interference Models

1) Protocol Interference Model: In the protocol interference model [5, 6], the existence of links and interference relationships between links are determined according to the location of node v_i, transmission range r_i and interference ratio α_i as follows. When two nodes $v_i, v_j \in \mathcal{V}^c$ are satisfied with $||v_i - v_j|| < r_i$, the communication from sender node v_i to receiver node v_j is successful, and the directed communication link $l_{i,j} \in \mathcal{E}^c$ is set. Here, $||v_i - v_j||$ stands for the distance between node v_i and node v_j. In addition, sender node v_i interferes with a link whose receiver node v_k satisfies $||v_i - v_k|| < \alpha_i r_i$. The interference ratio α_i is usually set between 2 and 4 depending on the environment [12].

2) SINR Model: Let sender node and receiver node be v_i and v_j. In addition, let $\mathcal{V}^{int}_{i,x}$ be the set of sender nodes that use the same time slot with link $l_{i,j}$ except node n_i. In the SINR model [6, 7], the existence of links and interference relationships among links are determined according to the SINR, which is defined as follows:

$$s_{i,j,x} = \frac{p_{i,j}}{p_{noise} + \sum_{v_k \in \mathcal{V}^{int}_{i,x}} p_{k,j}}. \quad (1)$$

Here, p_{noise} is the signal strength of noise, which is determined depending on the environment. $p_{i,j}$ is the received signal strength from sender node v_i at receiver node v_j, and is described as follows:

$$p_{i,j} = \frac{p^{tr}_i}{||v_i - v_j||^{\eta}}. \quad (2)$$

Here, p^{tr}_i is the transmission power of wireless signal at sender node v_i. η is the parameter for considering power decay due to distance, and is usually set between 2 and 4 depending on the environment [12].

In the SINR model, when SINR $s_{i,j,x}$ from Eq. (1) satisfies $s_{i,j,x} \geq B$, receiver node v_j can successfully receive radio signals from sender node v_i at time slot t_x. B is called the capture threshold which is determined depending on the wireless devices used. On the other hand, when SINR $s_{i,j,x}$ is less than threshold B, communication from sender node v_i to receiver node v_j fails. This means that the set of sender nodes $\mathcal{V}^{int}_{i,x}$ interferes with link $l_{i,j}$.

IV. METHODS FOR ADJUSTING THE INTERFERENCE RATIO PARAMETER OF THE PROTOCOL INTERFERENCE MODEL CONSIDERING SINR

In this section, we propose SINR-based methods for adjusting the interference ratio α_i parameter of the protocol interference model. Although the SINR dynamically changes in actual environments depending on fading, varying noise, etc., we assume static situation for simplicity in this paper.

A. Overview

Figure 2 shows the flowchart of our methods for adjusting the interference ratio. In our methods, transmission graph $\mathcal{G}^t$ is at first generated based on the protocol interference model. Information on interference relationships among transmission links are then determined based on the protocol interference model, where the interference ratio of all nodes is set to the initial interference ratio α_0. Next, a set of SINR $\mathcal{S} = \{s_{i,j,x} | l_{i,j} \in \mathcal{E}^t, t_x \in \mathcal{T}\}$ for all links which are used in all time slots is calculated. When the minimum SINR $s_{min} = \min \mathcal{S}$ is less than the capture threshold B, it means that there is a link which cannot be used in the SINR model. In this case, we adjust the interference ratio α, and then again determine the relationship of interference among transmission links and assign time slots based on the protocol interference model. This process is repeated until $s_{min} \geq B$ is satisfied. In the following, we propose three methods for adjusting the interference ratio.

B. Interference Ratio Adjustment Methods

1) All Nodes Adjustment (ANA) Method: In the ANA method, the interference ratio α_i of all nodes is adjusted by adding δ. Figure 3 shows an example transmission graph for the case of eight nodes and seven transmission links. Let transmission link $l_{7,4}$ have the minimum SINR in time slot t_w. In addition, let the time slot t_w be assigned to transmission links $l_{8,1}$, $l_{7,4}$, $l_{6,5}$ and $l_{3,2}$. In the ANA method, the interference ratio of all nodes, that is, v_1–v_8, are adjusted.

However, the ANA method is simple and increases the interference ratio of all nodes even if there is no difference

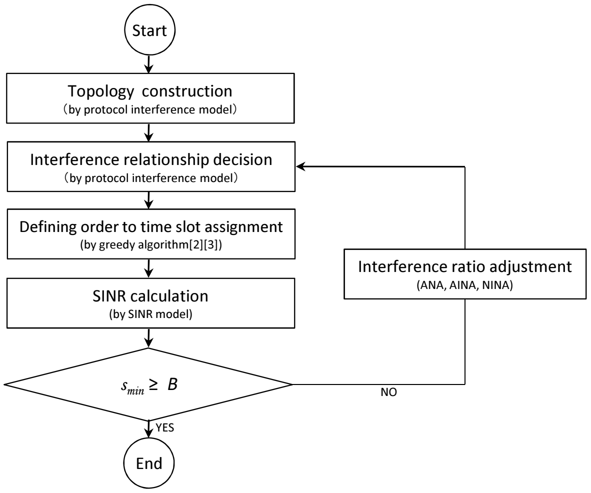


Figure 2. Flowchart for adjusting interference ratio

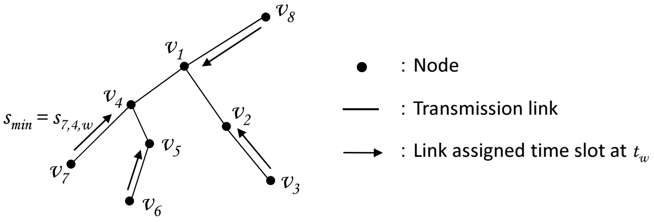


Figure 3. Example of transmission graph

in the result of the determined radio interference between the protocol interference model and the SINR model in a local region. If the interference ratio is increased more than necessary, more links are considered to have interference relationships, and the number of time slots is increased.

2) All Interference Nodes Adjustment (AINA) Method: In the AINA method, the interference ratio is adjusted locally. Let the SINR of transmission link $l_{g,h}$ in time slot t_w become the minimum SINR s_{min}, and the set of sender nodes which give interference to transmission link $l_{g,h}$ be $\mathcal{V}_{g,w}^{int}$. At transmission link $l_{g,h}$, there is the largest difference in the resulting interference relationship between the protocol interference model and SINR model. The AINA method adjusts the interference ratio of all nodes in $\mathcal{V}_{g,w}^{int}$ by adding δ. In the example of Fig. 3, the interference ratio of sender nodes v_3, v_6 and v_8, which are assigned the same time slot with transmission link $l_{7,4}$, are adjusted.

The AINA method adjusts the interference ratio of all sender nodes within $\mathcal{V}_{g,w}^{int}$. Therefore, it may increase the interference ratio of a node more than necessary when the node is far enough from a receiver node that has the minimum SINR.

3) Nearest Interference Node Adjustment (NINA) Method: In the NINA method, the interference ratio of the node that is the closest to the receiver node v_h, among the set of nodes $\mathcal{V}_{g,w}^{int}$, is adjusted by adding δ. In Fig. 3, node v_6 is the nearest from receiver node v_4, and the interference ratio of node v_6 is adjusted.

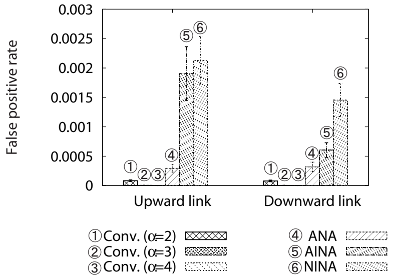
V. SIMULATION EXPERIMENTS

In this section, we evaluate the performance of our interference ratio adjustment methods through simulation experiments. We use a self-developed IEEE 802.16j mesh network simulator which is developed by Visual C. In the simulations, one gateway node is placed at the center and $n - 1$ nodes are randomly distributed in a 1×1 square area. We exclude the cases of a disconnected graph. In the protocol interference model, transmission distance r_i is set to 0.18. In the SINR model, transmission power p_i^{tr} and the parameter of power decay η are set to 1 and 3.0, respectively. Environment noise p_{noise} is set to 32, which is set when there are four nodes within a distance of 0.5 from the receiver node. Capture threshold B is set to 3 dB. In our proposed model, the initial interference ratio α_0 and the incremental ratio δ are set to 0 and 0.01, respectively.

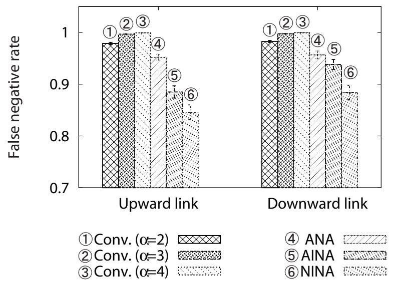
A. Evaluation of Accuracy

We first evaluate the accuracy of the protocol interference model using our proposed methods through a comparison with the SINR model. For all combination sets of transmission link $\mathcal{E}^t$, we evaluate whether a set of links has interference relationships for each radio interference model. Here, we exclude sets of transmission links where neighboring links are simultaneously selected. When both the SINR model and the proposed protocol interference model agree on whether or not a set of transmission links can be successfully used simultaneously, the proposed model's result is classified as a true positive or a true negative. When the SINR model produces the result that a set of transmission links can be used simultaneously and the proposed model produces the result that the set of transmission links cannot be used simultaneously, the proposed model's result is classified as a false negative. In the opposite case, its result is classified as a false positive. We adopt the *false positive rate* and *false negative rate* as measures of the accuracy of the radio interference model. False positive rate is defined as the number of false positives divided by the number of true negatives and false positives. False negative rate is defined as the number of false negatives divided by the number of true positives and false negatives. For comparison purposes, we also show the results for the protocol interference model where α is set to 2, 3 and 4. We refer to this as the *conventional method*.

Figure 4 shows the average of false positive rate and false negative rate with 99% confidence intervals from results for 100 topologies when $n = 50$. As shown in Fig. 4(a), the false positive rate for our proposed methods are larger than that for the conventional method. However, all of the false positive rate are quite low and are less than 0.22%. On the other hand, the false negative rate for the proposed methods decreases between 5% and 15% compared to that for conventional method as shown in Fig. 4(b). Among our proposed methods, the NINA method achieves the lowest false negative rate, while the ANA method has the highest

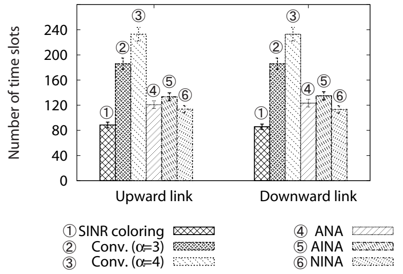


(a) False positive rate

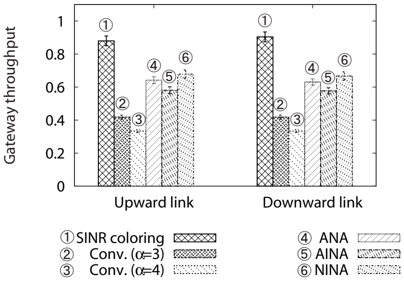


(b) False negative rate

Figure 4. Accuracy for all combinations of transmission link sets

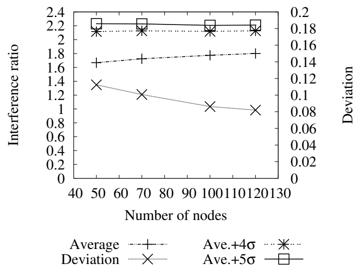


(a) Number of time slots

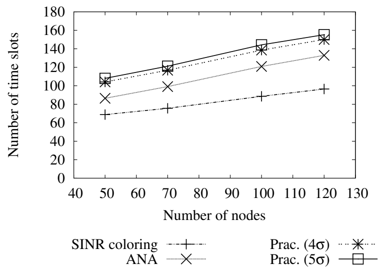


(b) Gateway throughput

Figure 5. Performance of a wireless mesh network



(a) Interference ratio



(b) Number of time slots

Figure 6. Practical interference ratio and its performance

false negative rate. Since the NINA method is designed not to increase the interference ratio more than necessary, the number of false negatives decreases and the number of true positives increases. As a result, the false negative rate for the NINA method becomes lower. However, the false negative rate for the NINA methods is still high, and is about 84% for upward links. This is due to the limitation of the protocol interference model which employs a binary decision of existence of radio interference based on a circular region.

When we compare the false positive rate and the false negative rate between upward links and downward links, the values are slightly different. In this paper, since we assume a tree topology whose root is the gateway node of the wireless mesh network, the number of sender nodes in upward communication is larger than that in downward communication. For example, leaf nodes become sender nodes in the case of upward communication. Therefore, the interference relationships among links become more complex in upward communication, and the results between upward links and downward links become slightly different.

B. Evaluation of the Network Performance

We next evaluate the performance of wireless mesh networks when the protocol interference model with our proposed methods is used. As evaluation metrics of performance, we use the *number of time slots* and *gateway throughput*. The former metric is the number of time slots required by the greedy algorithm [2, 3], and indicates the efficiency of spatial reuse. The gateway throughput is the number of assigned time slots to the gateway node in a frame, and it represents communication efficiency between the wireless mesh network and the external wired network. For comparison, we also conduct simulations where a SINR-based time slot assignment algorithm is used (hereinafter, SINR coloring). SINR coloring checks to assign a time slot to a transmission link in an order that is determined by the greedy algorithm. If the SINR of all transmission links are over the capture threshold by assigning the time slot to the transmission link, the time slot is assigned to the transmission link. Otherwise, a new time slot is assigned to the transmission link. Although SINR coloring is a time slot assignment algorithm, we use it as a method to achieve an upper bound of performance.

Figure 5 shows the average number of time slots and the average gateway throughput with 99% confidence intervals from results for 100 topologies when $n = 100$. Since there are links that cannot be used simultaneously under the SINR model but can be assigned based on the conventional method with $\alpha = 2$, we only show results for the conventional method where α is set to 3 and 4. As shown in Fig. 5, both the number of time slots and the gateway throughput of our proposed methods are closer to the results for SINR coloring than of the results for the conventional method. Among our proposed methods, the results for the NINA method are the closest to the results for SINR coloring. Because the accuracy of the interference model of the NINA method is the highest as described in the previous subsection, time slots are efficiently assigned to the links and communication efficiency becomes higher. When we compare the number of time slots and the gateway throughput between upward links and downward links, the results are almost same.

C. Discussion of Practical Interference Ratio

When we consider the usefulness of radio interference models, the models should be used without the calculation of SINR and time slot assignment. In particular, the interference ratio of the protocol model should be determined in advance. We call such previously decidable interference ratio the *practical interference ratio*. In this subsection, we investigate the practical interference ratio when all nodes use the same interference ratio, and evaluate the performance of wireless mesh networks with the practical interference ratio. Because the results for upward and downward links are similar, we only show the results for upward links.

We first conduct simulations of the ANA method and investigate the distribution of the adjusted interference ratio from 1000 topologies. The number of nodes n is set to 50, 70, 100, and 120. Although figures are not shown because of space limitations, the distribution of interference ratio becomes a normal distribution. The average and the standard deviation σ of the normal distributions are shown in Fig. 6(a). The maximum interference ratio is considered to be the average interference ratio plus $k\sigma$. The maximum interference ratio where $k = 4$ and $k = 5$ are also shown in Fig. 6(a). As shown in Fig. 6(a), the maximum interference ratio has a similar value for any number of nodes. Therefore, we use the average of the maximum interference ratios as the practical interference ratio in the following. In particular, we use 2.1 and 2.2 as the practical interference ratio in the case of $k = 4$ and $k = 5$, respectively.

Figure 6(b) shows the average number of time slots from the results for 100 topologies when the protocol interference model with the practical interference ratio is used. For comparison, we also show the results for the ANA method and SINR coloring. As shown in Fig. 6(b), the number of time slots using the practical interference ratio is greater than that of SINR coloring and the ANA method. In addition, the number of time slots using the practical interference ratio is 16% and 20% higher than that of ANA method when $k = 4$ and $k = 5$, respectively. This means that the accuracy of the protocol interference model using the practical interference ratio is less than that of the ANA method. However, by using the practical interference ratio, it is not necessary to calculate SINR or time slot assignment.

VI. CONCLUSIONS

To devise an accurate radio interference model, we proposed three methods, namely, ANA, AINA and NINA, for adjusting the interference ratio parameter of the protocol interference model, taking into consideration SINR. Through simulations, we showed that the NINA method achieves the highest accuracy. In addition, we found that the performance was highest in the case of a wireless mesh network based on the NINA method, among the proposed methods and the conventional method. Furthermore, we discussed the practical value of the interference ratio, which can be set without calculation of SINR and time slot assignment.

In future work, we plan to consider heterogeneous and dynamic cases where the transmission power of nodes is different and SINR is affected by Rayleigh fading and shadowing effect. In addition, we should take into account hop-based interference models, which are widely used in practical wireless networks, such as IEEE 802.16j networks. We plan to compare and investigate the relationships among the protocol interference model, the SINR model and the hop-based interference model.

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