An Implementation of Fixed Backoff-time Switching Method on IEEE 802.11 MAC Protocol for Wireless Internet-access Mesh Network

Nobuo Funabiki* Sritrusta Sukaridhoto* Zhe Wang* Toru Nakanishi* Kan Watanabe* Shigeto Tajima†
* Graduate School of Natural Science and Technology, Okayama University, Japan
{funabiki,nakanisi,can}@cne.okayama-u.ac.jp
† Graduate School of Engineering Science, Osaka University, Japan
tajima@ics.es.osaka-u.ac.jp

***Abstract*—A variety of aspects in the *Wireless Internet-access Mesh NETwork (WIMNET)* have been studied to provide a cost-efficient solution of a scalable Internet-access network. WIMNET is composed of multiple wireless *Access Points (APs)* to hosts that are also connected with each other through wireless links, where one AP acts as a gateway to the Internet. Previously, we have proposed the concept of the *CSMA-based Fixed Backoff-time Switching (CSMA-FBS) method* to improve the performance of WIMNET by assuring necessary link activation chances for multi-hop communications. In this paper, we present the detailed procedure of the CSMA-FBS method on the *IEEE 802.11 MAC protocol* and the implementation in the *QualNet* simulator. The simulation results in two network topologies confirm the effectiveness of our proposal.**

I. INTRODUCTION

A *wireless mesh network* has been extensively studied as a promising technology to flexibly and inexpensively expand the coverage area by allocating multiple wireless mesh routers on a network field [1]-[3]. As a scalable access network to the Internet using this technology, we have studied the architecture, protocols, and design optimizations of *Wireless Internet-access Mesh NETwork (WIMNET)* [3]-[5]. As shown in Fig. 1, WIMNET is composed of multiple access points (APs) as mesh routers that are connected with each other through wireless links. At least one AP acts as a *GateWay (GW)* to the Internet. Any host in WIMNET can be connected to the Internet through this GW using multihop communications between APs.

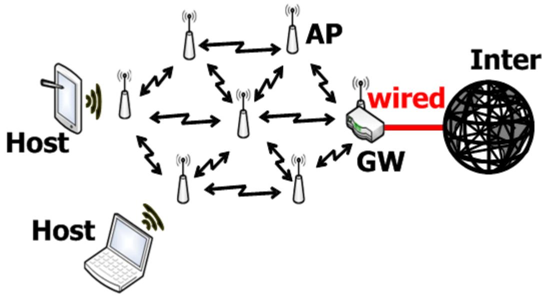

Fig. 1. Outline of WIMNET.

The wireless communication in WIMNET basically adopts the *IEEE 802.11 MAC (Media Access Control) protocol* [6]. To use a shared communication channel, a node in WIMNET employs the *CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol* in the IEEE 802.11 MAC. In CSMA/CA, any node possessing data packets for transmission is on standby during a random time before starting the data frame transmission to avoid frame collisions while providing the fairness among nodes. This standby time is called the *backoff-time*, and is assigned a random value within the *Contention Window (CW)*. When a node fails in the transmission, the CW size is increased to reduce the probability of the collision occurrence in the retransmission. When the node succeeds, it resets the CW size to the initial one.

Unfortunately, CSMA/CA may cause several problems when used in WIMNET. The first problem is the heavy congestion of the links around GW that can be bottlenecks of whole communications in WIMNET, because these links have to handle a lot of packets to/from GW for the Internet access. To avoid this problem, they should be activated with higher priorities than other links. The second problem is the interference among the links around GW that may not be resolved by the random backoff-time because of the limited CW size. Here, we note that the initial value of the CW size is small to reduce the idle time. Thus, multiple conflicting links can be activated at the same time by generating the same or similar backoff-time at transmitting nodes. In this case, any link cannot complete the packet transmission successfully, and needs reactivations that may cause further conflicts.

To solve these problems in WIMNET, we have previously proposed the CSMA-based *Fixed Backoff-time Switching (CSMA-FBS) method* [5]. In this method, the *target link activation rate*, the *active backoff-time*, and the *passive backoff-time* are assigned for each link on off-line before starting communications. The target link activation rate represents the frequency of activating the link that is necessary to handle the traffic properly in the multi-hop communication. The two types of backoff-times are assigned different values by following the descending order of expected traffic loads of the links. Here, a larger value than any active backoff-time must be set for the passive backoff-time, so that the link can be preferentially activated by using the active backoff-time.

During communications, the *actual link activation rate* is observed by counting the number of link activation chances and the number of actually activated times for each link, and by taking their fraction. If this value is smaller than the target one, the active backoff-time is selected at the link for the preferential activation. Otherwise, the passive backoff-time is used. Because any backoff-time is different from each other, conflicts among interfered links due to the same backoff-time can be avoided. However, in our previous study, only the concept of the CSMA-FBS method was presented and evaluated through our simple network simulator. The detailed procedure as a practical protocol was not implemented.

In this paper, we present the procedure of the CSMA-FBS method on the IEEE 802.11 MAC protocol and its implementation on a well-known network simulator *QualNet* [8]. QualNet has been known to adopt a more realistic physical model than other network simulators such as *ns-2* [9]. The evaluation using a realistic network simulator is significant to refine the details of this method before implementing it on hardware. Using QualNet, we show simulation results of our method and CSMA/CA in two network topologies, where they confirm the effectiveness of the CSMA-FBS method.

The rest of this paper is organized as follows: Section II reviews some related works. Section III introduces our previous proposal of the CSMA-FBS method. Section IV presents the implementation. Section V shows evaluation results on QualNet. Section VI concludes this paper.

II. RELATED WORKS

In this section, we introduce some related works to our study of the CSMA-FBS method for WIMNET.

In [10], Xu et al. raised the question: Can the IEEE 802.11 work well in wireless ad hoc networks ? They concluded that the protocol was not designed for multihop networks. Although it can support some ad hoc network architecture, it does not intend to support wireless multihop networks such as ad hoc networks and wireless mesh networks, where the connectivity is one of the most prominent features.

In [11], Minooei et al. proposed an efficient backoff mechanism for ad hoc networks using DCF. It decreases the CW size by 1 unit at the successful transmission after failures, instead of resetting the small initial value. For this purpose, the backoff-time bt is given by:

$$bt = rand\left[CW_{\min} \times 2^{m-1}, CW_{\min} \times 2^{m}\right] \tag{1}$$

where CW_{min} represents the initial contention window size, m does the number of consecutive transmission failures, and the function $rand\left[x, y\right]$ returns a uniformly randomized integer between x and y. The simulation results show the higher end-to-end throughput than the conventional IEEE 802.11 MAC protocol. In [12], Wu et al. modify the backoff time by considering the frame collision probability of each node for multihop ad hoc networks.

In [13], Nakamura et al. proposed the fixed backoff-time for wireless LANs. By simulations, they showed that it can reduce collisions and idle duration to improve the throughput and delay performance. However, their method is based on PCF, whereas WIMNET is based on DCF.

III. PREVIOUS PROPOSAL OF CSMA-FBS METHOD

In this section, we briefly describe our previously proposed CSMA-FBS method with the outline of the MAC protocol.

A. IEEE802.11 MAC Protocol

The IEEE802.11 MAC protocol makes it possible for several nodes to share the same physical medium or channel by detecting and/or avoiding data frame collisions. Fig. 2 illustrates the timing chart for the data transmission. After the channel becomes idle, the source node waits first for the DIFS period, and then, for the backoff-time that is randomly selected between 0 and the CW size. Then, if it does not detect any transmission from other node, it starts the transmission. The backoff-time is used to stagger the transmission timing among nodes to avoid collisions. If collisions occur, the CW size is doubled as the binary exponential backoff scheme to avoid further collisions. If the transmission succeeds, the CW size is reset to the initial one CW_{min}.

B. Overview of CSMA-FBS Method

Unlike the conventional MAC protocol using a random backoff-time, the CSMA-FBS method uses the two fixed backoff-times, namely the *active backoff-time* and the *passive backoff-time*, for each link to avoid the simultaneous activations of conflicting links. Either one of them is selectively used by comparing the *target link activation rate* and the *actual link activation rate*. On off-line before communications, any backoff-time is assigned a different value from each other so that any pair of conflicting links may not be activated at the same time. Besides, the backoff-time for a link with the larger traffic load is assigned a smaller value than that for a link with the smaller load, so that congested links can be activated more preferentially than less-congested links. Furthermore, any active backoff-time is assigned a smaller value than a passive one, so that links using active ones have larger priorities in activations than links using passive ones.

During communications, every time an AP holding packets detects that the channel becomes clear, it calculates the actual activation rate. If the value is smaller than the target activation rate of the link, it selects the active backoff-time because the actual activation rate of this link is not enough to handle the traffic. On the other hand, it selects the passive backoff-time so that other links selecting active backoff-times can be activated with higher priorities. The link with the passive backoff-time can be activated only if any conflicting link with the active backoff-time does not hold packets.

C. Target Activation Rate

On off-line, the *target activation rate* is calculated for each link by dividing the number of assigned time-slots for this link

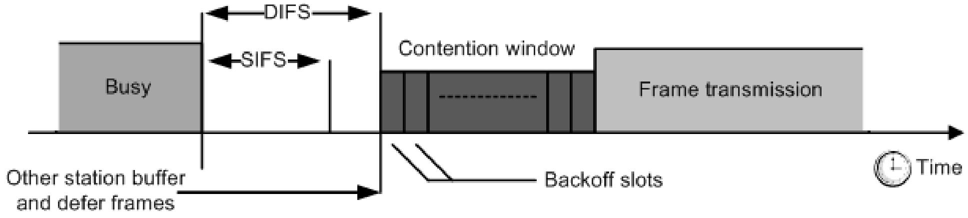

Fig. 2. Timing chart for data transmission.

activation in the TDMA cycle with the TDMA cycle length [5]. The *TDMA cycle* can be obtained by the link scheduling algorithm in [7]. The target activation rate rt_{ij} for link l_{ij} that transmits packets from AP_i to AP_j for $i = 1, \cdots, N$ and $j = 1, \cdots, N$ where N is the number of APs, is given by:

$$rt_{ij} = \frac{ts_{ij}}{T_{CL}} \tag{2}$$

where T_{CL} represents the TDMA cycle length, and ts_{ij} represents the number of assigned time-slots for link l_{ij}.

D. Active/Passive Backoff-time

The two fixed backoff-times for each link are calculated from the link priority. First, the number of hosts h_{ij} using link l_{ij} for communications, and the link priority p_{ij} are calculated by the following procedure:

1) Initialize h_{ij} by 0.
2) Add the number of hosts associated with AP_k to h_{ij} if the communication path between GW and AP_k includes l_{ij} for $k = 1, \cdots, N$.
3) Sort every link in the descending order of h_{ij}, where the tiebreak is resolved by the number of links relaying packets of the link.
4) Assign this sorted order to p_{ij} for l_{ij}.

Then, the two fixed backoff-times for each link are assigned by using the link priority. The active backoff-time ta_{ij} and the passive one tp_{ij} for link l_{ij} are given by:

$$ta_{ij} = p_{ij} \times \delta,\ tp_{ij} = (P + p_{ij}) \times \delta \tag{3}$$

where δ represents the unit backoff-time, and P does the largest priority among the links.

IV. IMPLEMENTATION OF CSMA-FBS METHOD

In this section, we present our implementation of the CSMA-FBS method on the IEEE 802.11 MAC, and the actual implementation on QualNet.

A. Actual Activation Rate

In the IEEE 802.11 MAC, the *actual activation rate* for each link is obtained by dividing the number of actually transmitted packets with the number of possible activation chances of the link:

$$ra_{ij} = \frac{pn_{ij}}{ac_{ij}} \tag{4}$$

where ra_{ij} represents the actual activation rate for link l_{ij} that transmits packets from AP_i to AP_j, pn_{ij} does the number of packets that have been successfully transmitted through link l_{ij}, and ac_{ij} does the number of possible activation chances of link l_{ij}.

In the IEEE 802.11 MAC using CSMA, ac_{ij} is hard to be measured precisely. One reason is that unlike the TDMA protocol where the link activations are synchronized by a single clock, the boundary of one link possible activation chance is not clear. Another reason is that the link activation chance resulting in the transmission failure should not be counted, because it is not considered in the calculation of the target activation rate.

In our implementation, we neglect the effect of this transmission failure for simplicity. Thus, ac_{ij} is incremented every time AP_i detects the channel clearance where no node is using the channel. Then, pn_{ij} is counted every time link l_{ij} starts transmitting a packet, where the success or failure is not considered.

In our implementation in QualNet, we added one necessary variable *dot11− >chance* in the function:
MacDot11AttempToGoIntoWaitForDifsOrEifsState
for pn_{ij}, and increased the value every time this function is called. Then, for ac_{ij}, we can get the value from the variable *dot11->pktsToSend*. By using two variables *node->nodeId* and *dot11->currentNextHopAddress*, we can obtain the link index ij of link l_{ij}.

B. Backoff-time Modification

For very crowded links that often appear around the GW in WIMNET, even slightly different backoff-times among these links in the CSMA-FBS method cannot avoid collisions of interfered links due to propagation delays in wireless links. In such situations, the difference of backoff-times among links should be enlarged to further stagger their transmission timing. Besides, the waiting time before starting the transmission should be long enough to detect activations of conflicting links as in [11][12]. Therefore, in our implementation of the CSMA-FBS method, any backoff-time is randomly selected between the minimum one and the maximum one that satisfy the following constraints for the CSMA-FBS method:

- Any active backoff-time must be smaller than any passive backoff-time.
- The backoff-time for a link with the higher priority must be smaller than that for a link with the lower priority.

Actually, the active backoff-time ta_{ij} for link l_{ij} with the priority p_{ij} is given by:

$$\begin{aligned} amin_{ij} &= CW_{\min} \cdot \left(2^{m-1} + 2^{m-2} \cdot \frac{p_{ij}-1}{P}\right), \\ amax_{ij} &= CW_{\min} \cdot \left(2^{m-1} + 2^{m-2} \cdot \frac{p_{ij}}{P}\right), \\ ta_{ij} &= rand\left[amin_{ij}, amax_{ij}\right], \end{aligned} \tag{5}$$

and the passive backoff-time tp_{ij} is given by:

$$\begin{aligned} pmin_{ij} &= CW_{\min} \cdot \left(2^{m-1} + 2^{m-2} \cdot \frac{P+p_{ij}-1}{P}\right), \\ pmax_{ij} &= CW_{\min} \cdot \left(2^{m-1} + 2^{m-2} \cdot \frac{P+p_{ij}}{P}\right), \\ tp_{ij} &= rand\left[pmin_{ij}, pmax_{ij}\right]. \end{aligned} \tag{6}$$

where m represents the number of consecutive transmission failures of a link and is saturated by 6. Once these backoff-times are assigned on off-line, they are fixed during communications in our implementation.

In the implementation in QualNet, we added the abovementioned procedures in the function *MacDot11StationSetBackoffIfZero*.

V. EVALUATION BY SIMULATIONS

In this section, we show evaluation results of the implementation of the CSMA-FBS method on the IEEE 802.11 MAC using the QualNet simulator.

A. Simulation Condition

For evaluations of our implementation of the CSMA-FBS method on the IEEE 802.11 MAC, we prepare two network topologies with static routing in Fig. 3 (Line topology) and Fig. 4, (Grid topology) in QualNet. The IEEE 802.11b protocol is adopted for any node where the nominal bit-rate is $5.5Mbps$ and the nominal wireless range is $250m$.

Each host performs CBR (Constant Bit Rate) as a real-time UDP application and FTP (File Transfer Protocol) as a TCP application destined for the GW, which indicate that only upstream flows exist. In CBR, 20 packets are transmitted from the source host to the GW at each second, where one packet size is changed from $160bytes$ to $2560bytes$. In FTP, data files with $160bytes$ to $2560bytes$ are transmitted from the source host to the GW at every $0.05sec$. The network simulation is executed for $30min.$, and the average result throughout the simulation is used in evaluations. The simulation condition is summarized in Table I.

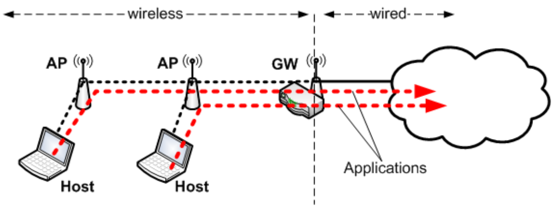

Fig. 3. Line topology.

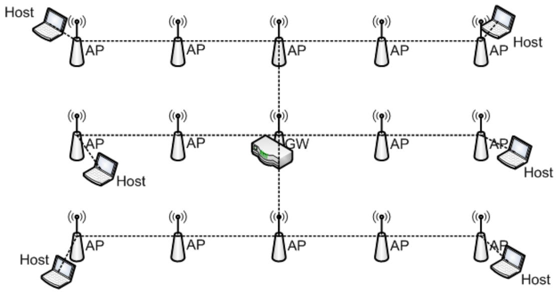

Fig. 4. Grid topology.

TABLE I
SIMULATION CONDITION.

parameter	value
protocol	IEEE802.11b
nominal bit-rate	5.5 Mbps
channel frequency	AP-AP: 2.484 GHz AP-host: 2.412, 2.437, 2.482 GHz
simulation time	30 min.
application	CBR for UDP FTP Generic for TCP
packet rate in CBR	20 packets/sec
packet size in CBR	160, 320, 640, 1280, 2560 bytes
File size in FTP	160, 320, 640, 1280, 2560 bytes

B. CSMA-FBS Parameter Setting

In this subsection, we briefly describe how to obtain the set of parameters for the CSMA-FBS method for simulations.

1) Target Activation Rate: In this paper, we adopt a simple method to calculate the target activation rate based on an assumption that every link can be interfered with each other in WIMNET. Then, at each time-slot of the TDMA cycle, only one link can be activated without conflicts so that the TDMA cycle length T_{CL} is equal to the total number of the one-hop links to transmit one packet from each host to the GW. The total number of links can be obtained as the summation of the hop count between each host and the GW. Then, for each link, the target activation rate rt is given by dividing the number of hosts using the link with T_{CL}.

For discussions, we assign a unique index to each link in the line topology: $L1$ for the link between the GW and the first AP, $L2$ for the link between two APs, $L3$ for the link between the first AP and the host, and $L4$ for the link between the second AP and the host. Then, the first host uses $L1$ and $L3$ to the GW, and the second host uses $L1$, $L2$, and $L4$. Thus, the total number of links is given by $2 + 3 = 5$ $(= T_{CL})$. Then, $rt = 2/5$ is set for $L1$, and $rt = 1/5$ is for the other three links.

Here, we should note that in our following simulations, we actually tripled the target activation rate for each link in line topology, because we found that this increase of the target activation rate improves the throughput. The reason may come from that we do not consider the link transmission failures due to conflicts. The link transmission failures nominally increase the number of transmitted packets pn in (4), which reduces chances of selecting the active backoff-time. However, the target activation rate for the grid topology was not changed in simulations. The optimization of the target activation rate for each instance will be in our future studies.

2) Link Priority and Backoff-times: The link priority p should be assigned to each link in the descending order of the number of hosts using the link. In the line topology, it is 2 for the link between the GW and the first AP, and 1 for the other links. Thus, $p = 1$ is set for $L1$, $p = 2$ for $L2$, $p = 3$ for $L3$, and $p = 4$ for $L4$, where any enumeration of the priorities for $L2$, $L3$, and $L4$ is actually acceptable. The largest priority P is 5. Then, the backoff-times for each link is obtained by applying the formulas in (5) and (6) with $CW_{\min} = 31$.

C. Performance Evaluation for Real-time Application

First, we evaluate the performance improvement of the CSMA-FBS method from the conventional CSMA/CA method in a real-time application using CBR.

1) Throughput: First, we compare the throughput between two methods when only CBR is used. Fig. 5 shows the average throughput where the packet size is changed from $160bytes$ to $2560bytes$. This result indicates that as the traffic load is low with the packet size of $160bytes$ or $320bytes$, their throughputs are similar, and when the traffic load is high with $1280bytes$ or $2560bytes$, the CSMA-FBS method improves the throughput by about 10% from the conventional one.

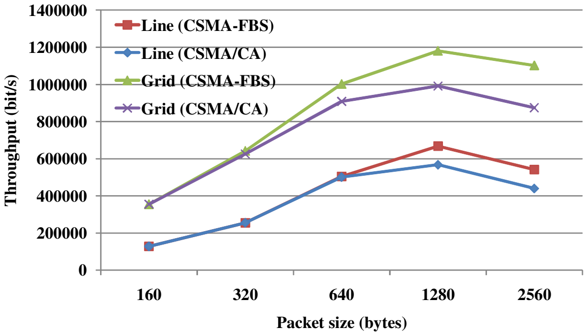

Fig. 5. Throughput.

2) Packet Loss: We compare the packet loss during communications between them. Fig. 6 shows the number of lost packets for the different packet size. This result indicates that as the traffic load increases, the packet loss also increases in both methods, where the CSMA-FBS method can slightly reduce it. Here, we note that packets are lost at the intermediate (relay) nodes, but not at sources.

3) End-to-End Delay: We compare the end-to-end delay from the source (host) to the destination (GW) between them. Fig. 7 shows the average delay from one host to GW among all the hosts and packets for the different packet size. This result indicates that as the traffic load increases, the delay also increases in both methods, where the CSMA-FBS method can reduce it by about 17%.

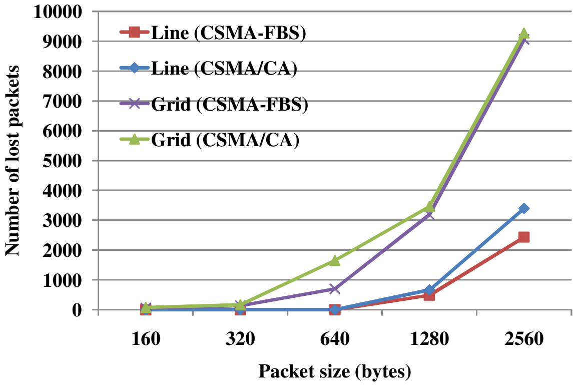

Fig. 6. Number of lost packets.

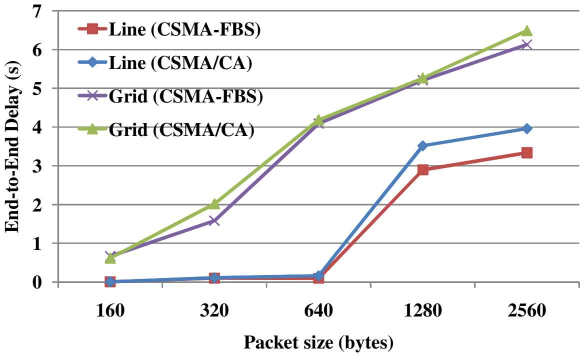

Fig. 7. End-to-end delay.

4) Queuing Time: Then, we compare the queuing time at a node between them. Fig. 7 shows the average queuing time among all the nodes and packets for the different packet size. This result indicates that as the traffic load increases, the queuing time also increases in both methods, where the CSMA-FBS method can slightly reduce it.

D. Throughput Fairness Evaluation for TCP Application

In WIMNET using the conventional CSMA/CA method, it has been observed that hosts closer to the GW in terms of hop counts occupy more bandwidth than hosts farer from the GW. Thus, a host may receive unfair services depending on the location in terms of the hop count from the GW. This throughput unfairness is another serious problem in WIMNET.

In order to evaluate the improvement in the fairness by the CSMA-FBS method, we measure the highest throughput and the lowest throughput among the hosts when all of them are executing the same FTP application. Figs. 9 and 10 show the highest and lowest throughputs among the hosts for each topology for the different packet size. These results indicate that the CSMA-FBS method can increase both throughputs in both topologies. Particularly for the grid topology, the

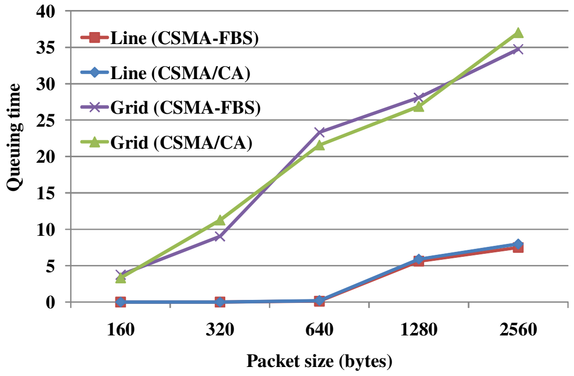

Fig. 8. Queuing time.

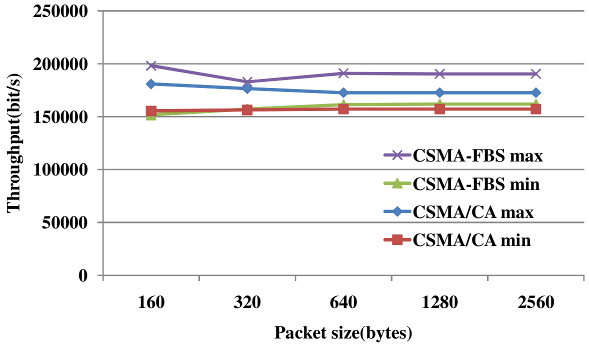

Fig. 9. Throughput fairness for TCP in Line topology.

CSMA/CA method cannot afford the FTP application for one host with $160 bytes$ where the minimum throughput becomes zero. On the other hand, our CSMA-FBS method can afford the application for any host.

However, the unfairness among hosts cannot be fully solved even by the CSMA-FBS method, where the difference between the highest and lowest throughputs is actually increased by the CSMA-FBS method. Thus, the improvement in the fairness will be also in our future studies of the CSMA-FBS method for WIMNET.

VI. CONCLUSION

This paper presented the procedure of the CSMA-based Fixed Backoff-time Switching (CSMA-FBS) method for wireless mesh networks on the IEEE 802.11 MAC protocol and the implementation in the QualNet simulator. The performance comparisons between the CSMA-FBS method and the conventional CSMA/CA method confirm the superiority of our method in the throughput, the packet loss, the delay, and the fairness. Our future works include the refinement of the actual activation rate and backoff-time calculations, the optimization of the target activation rate, the improvement in the throughput fairness, and the implementation of the CSMA-FBS method on hardware for evaluations in real networks.

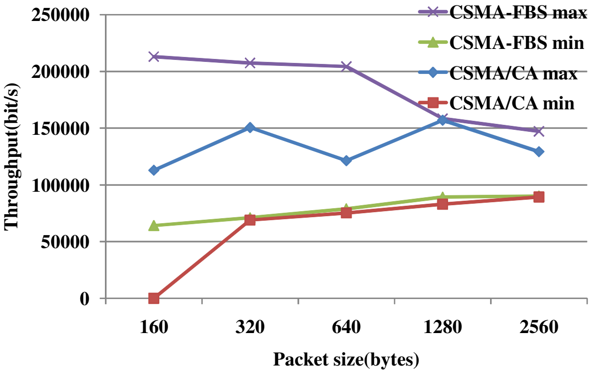

Fig. 10. Throughput fairness for TCP in Grid topology.

ACKNOWLEDGMENTS

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