Journal of Communications vol. 17, no. 8, August 2022

A Throughput Fairness Control Method for Concurrent Communications in Wireless Local-Area Network with Multiple Access-Points

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Abstract—The *IEEE 802.11n wireless local-area network (WLAN)* has been widely deployed at every place around the world for the Internet access services. In WLAN, the *throughput unfairness problem* appears among concurrently communicating hosts due to their signal strength differences when the distances to *access-points (APs)* are different. Previously, to achieve fair network services among users, we have studied the method of controlling the *packet transmission delay* at one AP using *PI controller*. However, it cannot be applied to multiple APs that are common in WLAN. In this paper, we propose a *throughput fairness control method* of applying *traffic shaping* at the APs to provide the fair throughput among concurrently communicating hosts with multiple APs. For evaluations, we implement the testbed system using *Raspberry Pi* for APs and conduct extensive experiments in six topologies with up to four APs. The results show that the throughput of every host is similar to each other in any topology, which confirms the effectiveness of the proposal.

Index Terms—WLAN, traffic shaping, throughput fairness, Raspberry Pi, PI controller

I. INTRODUCTION

Currently, the *IEEE802.11 wireless local-area network (WLAN)* is the most popular medium for the Internet access around the world [1]-[3]. WLAN offers several benefits such as coverage range flexibility, high data transmission speeds, and easy installations due to no cable requirements between the host and the *access point (AP)*. Hence, it has been deployed at offices, schools, and public transportations including buses, trains, and airplanes [4], [5].

In WLAN, the fair throughput service is important to offer the equal *quality of service (QoS)* among the hosts in the network. Particularly, as the demand for real time multimedia application increases such as online meeting tools, the fairness becomes the critical issue. However, in principle, WLAN cannot ensure the fair throughput service among the hosts in the network. The different distances between hosts and their associated APs will cause different throughputs among them, because different *received signal strengths (RSSs)* are observed at the receivers. Besides, the interferences among co-located APs and hosts in the same network field can enhance the throughput differences.

Previously, to realize the fair throughput service among the multiple hosts associated with a single AP, we studied the method of controlling the *packet transmission delay* at the AP using *PI control* [6]. Unfortunately, this method was limited to one AP in the network, although multiple APs are common and are often interfered with each other in WLAN. Our previous method initially calculates the *packet transmission delay* based on measured RSS of the hosts. Then, it dynamically changes the *delay* using the *PI controller* to achieve the fair throughput among the hosts. This feedback control can result in the slow convergence to achieve the fair throughput. Besides, it cannot calculate the proper target throughputs for the hosts when they are concurrently communicating with different APs.

In WLAN, multiple APs are often deployed in the network to provide the flawless Internet access by extend the network coverage range, and to support a large number of hosts. *Channel Bonding (CB)* has been introduced in WLAN to increase the transmission capacity by combining two adjacent 20MHz channels to form a single 40MHz channel [7]. In WLAN using multiple APs and CB channels, it has been observed that the throughputs are much different among concurrently communicating hosts due to their unequal *RSS* and interferences if the distances between the hosts and the APs are different. The hosts far from the APs receive lower *RSS* than the hosts near to them, which leads to the use of a slower *modulation and coding scheme (MCS)* and to the lower throughputs. As a result, the throughput unfairness problem becomes serious among the hosts.

In this paper, we propose a *throughput fairness control method* to solve the throughput unfairness problem in general WLAN using multiple APs. It provides the fair throughput to every host in WLAN, when they are concurrently communicating with different APs. First, this method derives the *target throughput* for the throughput fairness by measuring the *single and concurrent throughputs* and estimating the *channel occupying time* for each host. Then, it achieves the fair throughput by applying *traffic shaping* using the *traffic control (tc)* command [8] at the Linux-based AP. It is noted that this command actually adopts the *Hierarchical Token Bucket (HTB)* queuing discipline.

Manuscript received January 15, 2022; revised July 10, 2022.
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doi:10.12720/jcm.17.8.592-599

For evaluations, we implemented the proposal in the *WLAN testbed system* that uses *Raspberry Pi* devices for the APs, and conducted extensive experiments in six network topologies with up to four APs. The experiment results show that the throughput fairness becomes close to 1 in any topology, which confirms the effectiveness of our proposal.

The rest of this paper is organized as follows: Section II discusses related works in literature. Section III reviews preliminaries to this study. Section IV proposes the throughput fairness control method. Section V evaluates the proposal through experiments. Finally, Section VI concludes this paper with some future works.

II. RELATED WORKS IN LITERATURE

In this section, we briefly discuss related works in literature. Several research studies discuss about throughput fairness to ensure QoS in WLAN.

In [9], Hwang *et al*. studied the fair throughput allocation issue in a multi-rate WLAN. Hence, they proposed a network-wide association scheme with traffic control that defines the possible data traffic from an access point to clients based on throughput allocation algorithm. The proposal is verified by simulation. In contrast, our approach is implemented at the AP by using conventional Linux command.

In [10], Abuteir *et al*. proposed a *software defined networking (SDN)* based *wireless network assisted video streaming (WNAVS)* method to ensure the fairness among the stations. The proposal uses traffic shaping to control packets based on bandwidth allocation for users and network traffic statistics. However, their methods are limited to video applications and cannot allocate the equal throughput. In contrast, our approach is generic for applications and ensure the fair throughput among the users.

In [11], Lei *et al*. presented a *fair bandwidth allocation* approach, which allocates the bandwidth based on the user needs and priority. Then, they adopted association algorithm based on client demands, which selects the optimal associating AP according to transmission time demanded by all the associating clients. This method does not provide fair throughput when multiple APs are concurrently communicating with the hosts.

In [12], [13], Fang *et al*. and Kongsili *et al*. considered the air-time assignment policy for proportionally allocating the fair throughput to the hosts in WLAN while increasing the overall network throughput. On the other hand, our approach allocates a equal throughput to the concurrently communicating hosts in WLAN with multiple APs.

In [14], Mansy *et al*. presented a *quality of experience (QoE)* metric for adaptive video streams to ensure fairness at the network layer. They designed a max-min fairness problem based on this QoE metric to enforce throughput allocations in the home network. The traffic shaping is adopted to control the data traffics.

In [15], Høiland-Jørgensen *et al*. presented a network layer queue management scheme to ensure the proportional fairness among the competing hosts in WLAN while increasing the overall throughput. However, their approach cannot ensure the equal throughput performance among the hosts. It was implemented at the AP with no modification at the MAC layer protocol.

In [16], Blough *et al*. dealt with interference aware proportional fairness in dense WLANs by considering the *signal to noise ratio (SNR)* level at receiving stations. In their approach, the SNR is used to estimate the optimum data transmission rate based on the channel condition in order to allocate fair throughput among the competing hosts. While this method can increase network throughput, there is still a problem with throughput allocation among the hosts when considering equal throughput performance.

In [17], Yan *et al*. investigated the performance anomaly problem in multi-rate WLAN. Thus, they proposed a MAC optimization technique for maintaining proportional throughput fairness by altering the contention window based on data rate and packet size. It was implemented at the MAC layer and verified by simulations. In contrast, our approach is implemented in the real testbed system and ensure the fair throughput among the hosts when they are concurrently communicating with different APs.

Most of the works in literature focus on the fairness among hosts when they communicate with one AP. They do not consider multiple APs. On the other hand, our proposal consider multiple APs in WLAN, adopts simple Linux commands for easy implementations on real devices, and is evaluated through experiments using real devices.

III. PRELIMINARY

In this section, we introduce preliminaries to this study.

A. Throughput Unfairness Observation

In WLAN, the throughput unfairness may appear among concurrently communicating hosts due to their *received signal strength (RSS)* differences when the distances to APs are different.

Previously, we conducted experiments of measuring the throughputs of three concurrently communicating hosts with three different APs. Fig. 1 shows the experiment field in the third floor of Engineering Building #2 at Okayama University. The host locations are depicted by the circles and the AP locations are by the tringles.

H_1 was connected with AP_1, H_2 was with AP_2, and H_3 was with AP_3. The distance between the host and the AP was different from each other. The *IEEE802.11n* protocol was adopted with 40MHz bonded channels at 2.4GHz. To reduce the interferences as much as possible, the three bonded channels, 1 + 5, 9 + 13, and 5 + 9, are assigned to AP_1, AP_2, and AP_3, respectively, by following the assignments in [18].

Then, as shown in Fig. 2, the *throughput unfairness* among the hosts was observed. The distance between AP_2

and H_2 was shortest. Thus, the throughput of the link $AP_2 – H_2$ was largest among the three links. On the other hand, the throughput of the link $AP_1 – H_1$ was smallest because the distance was longest and the elevator attenuated the signal as the obstacle of the transmission path. However, it is desired that the *throughput fairness* among them should be available even in this network with the objective of universal services among the users.

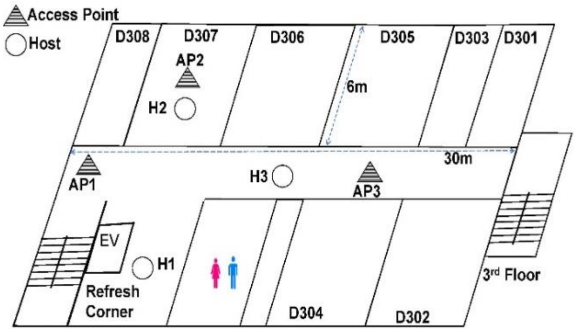

Fig. 1. Experiment field.

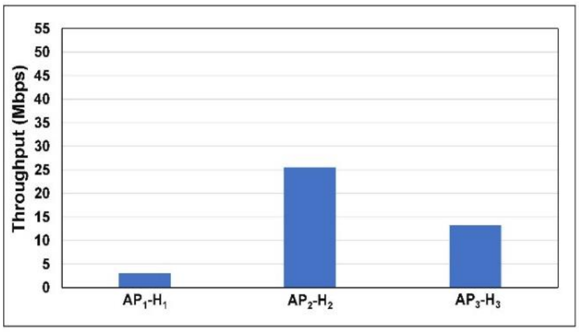

Fig. 2. Throughput unfairness observations in dense WLANs at concurrent communication.

B. Throughput Measurement Tool

In the proposal, the network monitoring tool *iftop* [19] is installed at the AP to measure the throughput of the link. The *iperf* [20] is used together to generate TCP traffics with the 8KB buffer size and the 477KB TCP window size.

C. Traffic Shaping

In the proposal, *traffic control (tc)* command in Linux is installed at the AP to control network traffics at the target rate by using *traffic shaping*. In general, network traffics can be controlled through three components: *queueing discipline (qdisc)* scheduler, classes, and filters. There are two types of qdisc schedulers: *classless qdisc* and *classful qdisc*. In this proposal, the link sharing hierarchy *classful HTB qdisc* is adopted to control network traffics at the certain rate by using two parameters namely, *ceil* and *rate*. The *rate* is the guaranteed bandwidth to the class and the *ceil* is the maximum amount it can get. In this proposal, the same value is assigned to them.

D. Jain's Fairness Index

The *Jain's fairness index* [21] represents the fairness among several numbers by a value between 1 and 0. 1 indicates that they are totally fair, and 0 does not at all. It is given by:

$$fairness\ index = \frac{(\sum_{i=1}^{n} x_i)^2}{n \times \sum_{i=1}^{n} x_i^2} \qquad (1)$$

where n represents the total number of numbers (hosts in this paper) and x_i does the i-th number value (throughput in this paper).

IV. PROPOSAL OF THROUGHPUT FAIRNESS CONTROL METHOD

In this section, we propose the throughput fairness control method using *traffic shaping* in WLAN.

A. Observations for Proposal

The proposed method is designed from the following observations:

a) The throughput of each host can be controlled by running *tc* at the *Linux-based* AP.

b) The *maximum number of transmitted bits per second (bps)* for each host can be measured by running *iftop* at the AP when only one AP is active and communicating with a single host, which is called the *single throughput*.

c) The *actual number of transmitted bits per second* for each host can be measured by running *iftop* at each AP when all the hosts are concurrently communicating, which is called the *concurrent throughput*.

d) The *target throughput* for each host is represented by the number of bits to be transmitted per second.

e) The *channel occupying time* per second for each host can be estimated by dividing the *concurrent throughput* or the *target throughput* with the *single throughput* when all the hosts are concurrently communicating.

f) The sum of the *channel occupying time* by every host can be constant (basically, one second).

g) The *target throughput* for each host cannot exceed the *single throughput*.

h) The *target throughput* that is larger than the *concurrent throughput* for a host can be realized by taking the *channel occupying time* of the other hosts, which determines the proper *target throughput* for each host.

B. Channel Occupying Time of Hosts

Let S_i and C_i be the measured *single throughput* and the measured *concurrent throughput* for the host H_i for $i = 1, 2, ..., n$, respectively. When all the hosts are concurrently communicating through the shared channel, the channel occupying time by each host during one second can be estimated by $\frac{C_1}{S_1}, \frac{C_2}{S_2}, ..., \frac{C_n}{S_n}$. Then, the summation of them will become constant, basically one second, as follows:

$$\frac{C_1}{S_1} + \frac{C_2}{S_2} + \cdots + \frac{C_n}{S_n} = Constant \qquad (2)$$

C. Equal Target Throughput

Here, we discuss the calculation of the target throughput when all the hosts be assigned the same target throughput: $t_1 = t_2 = ... = t_n$. Then, the channel occupying time for the hosts will be $\frac{t_1}{S_1}, \frac{t_2}{S_2}, ..., \frac{t_n}{S_n}$. From Eq. (2), the following result is obtained:

$$\frac{C_1}{S_1} + \frac{C_2}{S_2} + \cdots + \frac{C_n}{S_n} = \frac{t_1}{S_1} + \frac{t_2}{S_2} + \cdots + \frac{t_n}{S_n},$$

$$t_1 = t_2 = \cdots = t_n = \frac{\sum_{i=1}^{n} \frac{C_i}{S_i}}{\sum_{i=1}^{n} \frac{1}{S_i}} \quad (3)$$

Eq. (3) can be applied for any number of APs in the network.

D. PI Controller for Rate and Ceil Parameter

Traffic shaping cannot guarantee the assigned throughput d_i to the host that is set for *rate* and *ceil*. It only guarantees the maximum throughput. Then, the measured throughput of the host may fluctuate during communications using *traffic shaping* under the maximum one.

To address this inconvenience, the *PI control* [22] is adopted to dynamically adjust d_i in order to make the measured throughput equal to the target one using the following equation:

$$d_i(m) = d_i(m-1) + K_P \times \left(R_i(m-1) - R_i(m)\right) + K_I \times \left(t_i - R_i(m)\right). \quad (4)$$

where $R_i(m)$ does the measured throughput at time step m, and K_P and K_I express the *proportional (P)* and *integral (I)* control gain respectively ($K_P = 0.4$, $K_I = 0.5$ in this paper). The *time step* represents the time interval (60sec in this paper). To abstain the frequent changes of d_i, the *PI control* is used only when the throughput error $|R_i(m) - t_i|$ is greater than the given threshold $\alpha \times t_i$ for three continuous time steps and $\alpha = 0.2$ does the constant parameter.

E. Application of Traffic Shaping

In the testbed system, *traffic shaping* is implemented at the *Raspberry Pi* APs using the following procedure:

(1) Create the *HTB qdisc*, generate the necessary number of classes for every host *i*, and assign the *rate* and *ceil* value d_i by:

- $sudo tc qdisc add dev wlan1 root handle 1: htb default.
- $sudo tc class add dev wlan1 parent 1: classid 1:1 htb rate $\sum_{i=1}^{n-1} d_i$.
- $sudo tc class add dev wlan1 parent 1:1 classid 1:i htb rate d_i ceil d_i .

(2) Apply the d_i to the host H_i by specifying the IP address:

- $sudo tc filter add dev wlan1 protocol ip parent 1:0 prio 1 u32 match ip dst *IP of* H_i flowid 1:*i*.

F. Throughput Fairness Control Method Procedure

The following procedure illustrates the proposed throughput fairness control method:

a) Measure the *single throughput* for each host by activating only one AP and communicating it with the host.
b) Measure the *concurrent throughput* for every host by activating all the APs and communicating them with their associated hosts simultaneously.
c) Derive the equal *target throughput* t_i to a host.
d) Allocate t_i to every host by assigning $d_i = t_i$.
e) Apply *traffic shaping* using the *tc command.*
f) Measure the throughput for every host periodically while all the APs are concurrently communicating.
g) Apply *PI control* to update d_i.

V. EVALUATIONS

In this section, we evaluate the proposal through extensive experiments using the testbed system with up to four APs and four hosts. Each AP is connected with one host.

A. Experiment Setup

Fig. 3 shows the device configuration of the testbed system. Table I shows the hardware and software specifications. Raspberry Pi 3 *with TP-Link TL-WN722N wireless NIC* [23] adapter was adopted as the software AP. *Linux* laptop PCs were used for both the management server and hosts. The experiments for evaluations were conducted in the same field in Fig. 1. Table II shows the locations of the hosts and the APs and the channel assignments in the experiments. Considering fluctuations of measured throughputs, the measurements were conducted *12min* for each of six topologies, and their average results were used in evaluations.

TABLE I: DEVICE AND SOFTWARE SPECIFICATIONS

access point	
model	Raspberry Pi 3
CPU	BCM2837 1.2GHz, Broadcom
RAM	LPDDR2 900MHz 1GB
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd, iftop
server PC	
Model	Fujitsu Lifebook S761/C
CPU	Intel Core i5-2520M @2.5Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	Iperf 2.0.5
host PC	
model	1. Toshiba Dynabook R731/B 2. Toshiba Dynabook R734/K
CPU	1. Intel Core i5-2520M @2.5Ghz 2. Intel Core i5-4300M @2.6Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	Iperf 2.0.5

TABLE II: HOST AND AP LOCATIONS WITH CHANNEL ASSIGNMENTS

topology	number of APs	channel assignment				host and AP location							
		AP_1	AP_2	AP_3	AP_4	AP_1	H_1	AP_2	H_2	AP_3	H_3	AP_4	H_4
1	two	1 + 5	9 + 13	-	-	D307	In front of D307	D307	D307	-	-	-	-
2	two	1 + 5	9 + 13	-	-	In front of D307	D307	D307	D307	-	-	-	-
3	three	1 + 5	1 + 5	9 + 13	-	D307	D307	D307	D307	D307	D307	-	-
4	three	1 + 5	9 + 13	5 + 9	-	In front of D308	refresh corner	D307	D307	In front of D305	In front of D305	-	-
5	four	1 + 5	9 + 13	4 + 8	7 + 11	In front of D308	In front of D308	D307	refresh corner	D306	D306	In front of D301	In front of D301
6	four	1 + 5	9 + 13	4 + 8	7 + 11	In front of D308	In front of D308	D307	refresh corner	In front of D305	D306	refresh corner	refresh corner

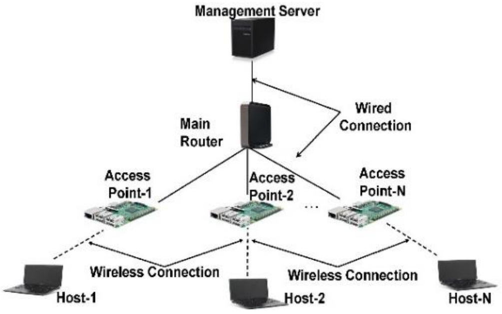

Fig. 3. Device configuration of testbed system.

B. *Throughput Results*

Fig. 4 to Fig. 9 show individual throughput results for the six topologies, respectively. Two APs, three APs, or four APs are concurrently communicating with hosts. In each figure, *single thr.* represents the measured single throughput, *concurrent thr.* does the concurrent throughput when all the hosts are communicating, *target thr.* refers to the target throughput that is given by the proposal, and *measur. thr.* does the measured throughput. From these graphs, we can observe the following results:

1) Two Aps

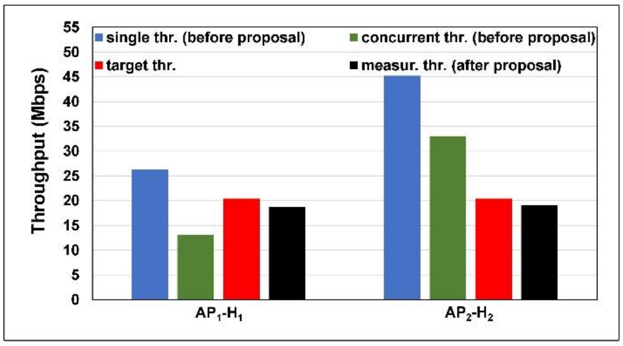

Fig. 4. Throughput results for topology 1.

First, we discuss the experiment results in topologies 1 and 2 where two APs are concurrently communicating with two hosts. Fig. 4 and 5 show the throughput results. With the proposal, the throughput fairness was successfully achieved among the hosts. In contrast, without the proposal, the equal throughput was not achieved. However, the average measured throughput was 94.03% of the target throughput. This reduction will come from the overhead of applying *traffic shaping* at the APs.

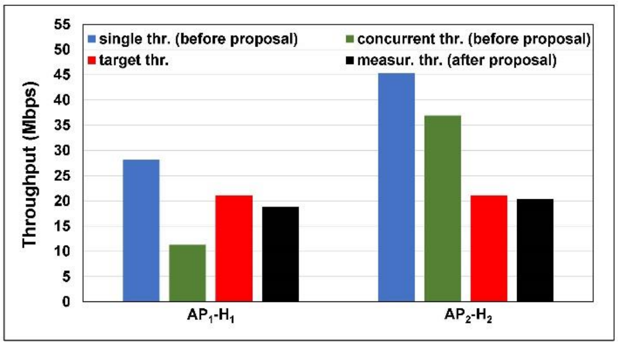

Fig. 5. Throughput results for topology 2.

2) Three APs

Next, we discuss the experiment results in topologies 3 and 4 where three APs are concurrently communicating with three hosts. Fig. 6 and 7 show the throughput results. The measured throughput after the proposal was similar among the hosts. The average measured throughput was 88.95% of the target throughput, where the overhead of applying traffic shaping at more APs became larger.

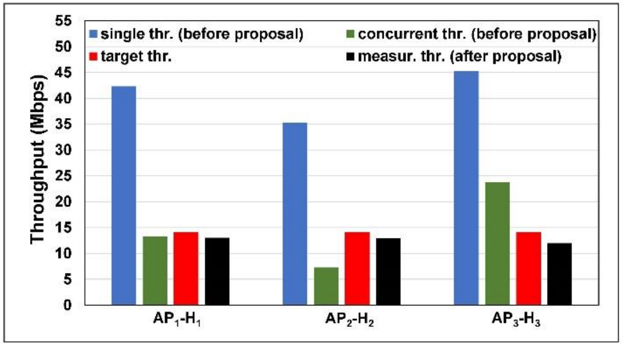

Fig. 6. Throughput results for topology 3.

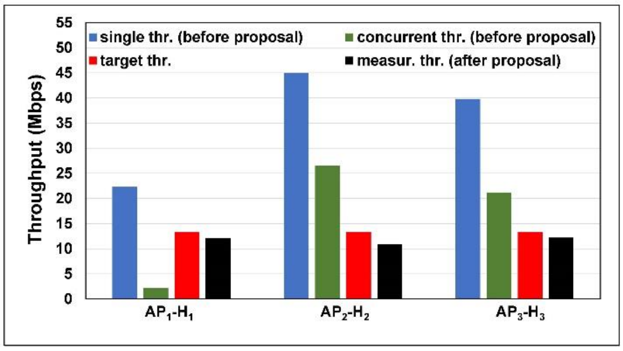

Fig. 7. Throughput results for topology 4.

3) Four APs

Finally, we discuss the experiment results in topologies 5 and 6 where four APs are concurrently communicating with four hosts. Fig. 8 and 9 show the throughput results. Again, the measured throughput after the proposal was similar among the hosts. The average measured throughput was further reduced to be 76.42% of the target throughput. Thus, the throughput enhancement at the increasing number of APs will be in future works.

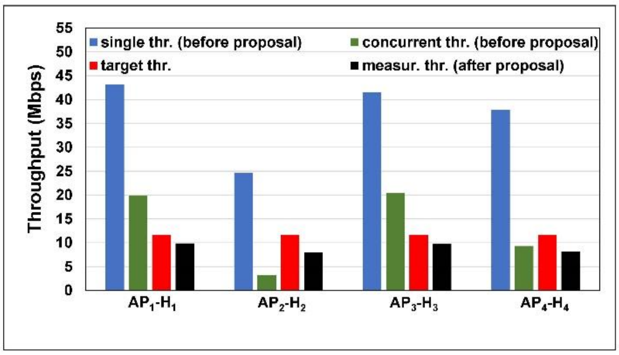

Fig. 8. Throughput results for topology 5.

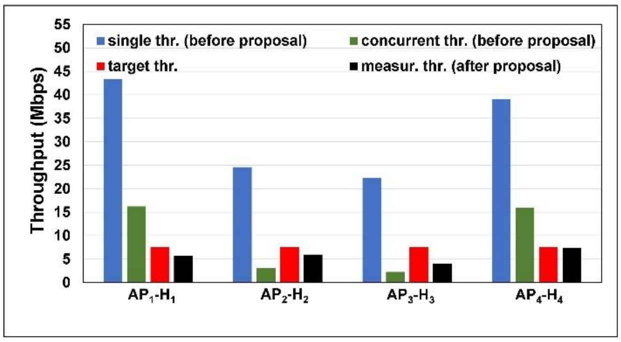

Fig. 9. Throughput results for topology 6.

C. Fairness Index

Table III compares the *Jain's fairness index* of the measured throughputs among the hosts and their totals. In any topology, this index becomes very close to 1 with the proposal, whereas it is much smaller than 1 without the proposal. However, the total throughput with the proposal is smaller than that without the proposal, because the proposal gives higher chances for slower hosts to transmit packets than for faster hosts. The solution of this tradeoff will be in future studies.

TABLE III: FAIRNESS INDEX AND TOTAL THROUGHPUT COMPARISONS

topology	fairness index		total throughput	
	without proposal	proposed approach	without proposal	proposed approach
1	0.841	0.999	46.10	38.77
2	0.779	0.999	48.18	39.23
3	0.823	0.998	44.28	37.84
4	0.718	0.999	49.92	35.22
5	0.768	0.990	52.78	34.65
6	0.662	0.970	37.50	22.89

VI. CONCLUSION

This paper presented the *throughput fairness control method* for concurrently communicating multiple hosts in a wireless local area network (WLAN) with multiple access-points (APs). The proposal adopts *traffic shaping* to control packet transmissions at the APs to the slower hosts to achieve the equal target throughput that is derived by measuring the single and concurrent throughputs. The proposal was implemented using *tc* command and *PI controller* in the WLAN testbed system using Raspberry Pi for APs. The effectiveness was confirmed through experiments in six topologies with up to four APs where each AP is connected to a single host in any topology. The extensive experiment results confirmed that the proposal achieved the fair throughput by allocating the equal target throughput to the hosts. In future works, we will study the throughput enhancement at the increasing number of APs, generalize the proposal to consider multiple hosts for each AP and the host mobility in the network, and verify them in various network fields and topologies.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

M. M. Rahman designed the algorithm, implemented the system, conducted experiments, and wrote the paper; N. Funabiki supervised the research and revised the paper; K. I. Munene and S. C. Roy took part in conducting experiments; M. Kuribayashi co-supervised the research; W.-C. Kao analyzed the paper and checked the grammatical errors; all authors had approved the final version.

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