Internet of Things 8 (2019) 100089

Contents lists available at ScienceDirect

Internet of Things

journal homepage: www.elsevier.com/locate/iot

Research article

A dynamic access-point transmission power minimization method using PI feedback control in elastic WLAN system for IoT applications

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A R T I C L E I N F O

Article history:
Received 29 July 2019
Accepted 3 August 2019
Available online 22 August 2019

Keywords:
Wireless LAN
Internet of Things
Access point
Transmission power minimization
RSS
PI control

A B S T R A C T

Nowadays, *Internet of Things (IoT)* has become popular in various applications, such as smart home networks, smart city networks, and smart grid systems. The *IEEE802.11n wireless local-area network (WLAN)* is one of major communication technologies relevant to IoT applications due to the flexibility and cost efficiency, where the efficient power management is a key requirement of emerging IoT applications. Previously, we have studied the *elastic WLAN system* with the *access-point (AP) transmission power minimization method* using the *throughput estimation model*, to minimize the power consumption of WLAN while ensuring the throughput performance. However, this method relies on the accurate model, which requires a lot of throughput measurements in the target field. In this paper, to avoid extensive measurements, we propose another AP transmission power minimization method using *PI feedback control*. The initial power is examined from the difference between the measured *received signal strength (RSS)* at the AP from the station or node and the estimated RSS necessary for the target throughput. Then, the power is minimized by using the PI control, such that the measured throughput achieves the target one. For evaluations, we implement the proposal in the *elastic WLAN system testbed* using *Raspberry Pi* devices that have been adopted in many IoT applications, and conduct experiments with five topologies. The results confirm that the proposal has significantly reduced the transmission power while achieving the target throughput.

1. Introduction

Nowadays, *Internet of Things (IoT)* has become popular with technological revolutions in wireless communications and networking. IoT introduces many protocols, techniques, and applications together to build a large network composed of a huge number of communicating devices, to provide various communication services, such as smart home networks, smart city networks, and smart grid systems [1,2].

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https://doi.org/10.1016/j.iot.2019.100089
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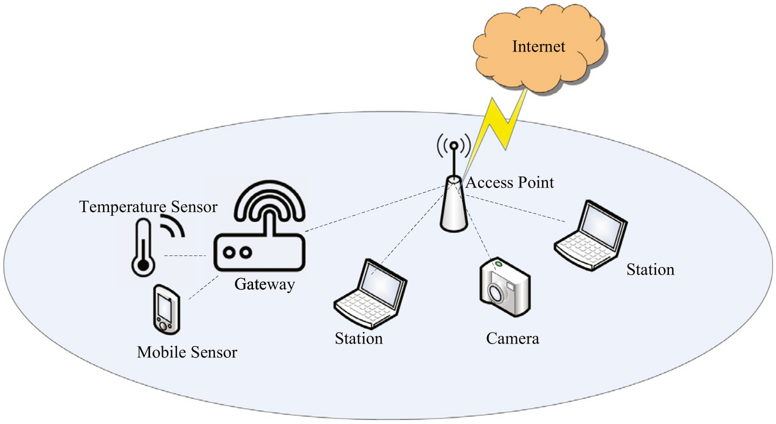


Fig. 1. Wireless local-area network for IoT application.

In the domain of IoT applications, current wireless technologies, such as the *wireless local-area network (WLAN)*, the *wireless sensor network (WSN)*, and *Bluetooth*, can play significant roles [3–5]. Actually, a lot of IoT applications adopt client-server type communications using WLAN, as shown in Fig. 1 [4,5]. Then, reducing the power consumption of WLAN is one of the key requirements for practical IoT applications, because they often run on networks with a large number of devices. From now on, in this paper, we use *station* and *node* interchangeably to represent a wireless device in IoT.

The popularity of the *IEEE 802.11 WLAN* has remarkably increased, since the wireless communication between an *access point (AP)* and a station offers flexible, scalable, and accessible connection services to the Internet [6,7]. WLAN services are available in offices, schools, and a large number of public places, such as hotels, airports, malls, stations, and even in trains and airplanes. In WLAN, the distribution of users or stations and traffics is mostly non-uniform and non-stationary [8], unpredictable [9], and will fluctuate depending on the time and day of the week [7]. The conditions of network devices and communication links may also be affected by various factors, namely, power shortages, device failures, bandwidth controls by the authorities, and weather changes [10]. To solve the aforementioned problems, we have studied the *elastic WLAN system* using heterogeneous AP devices [11–13]. This system optimizes the number of active APs, depending on the traffic demands and device conditions. Moreover, it minimizes the power consumption by deactivating unnecessary APs, while ensuring the required throughput. For this objective, we have proposed the *active AP configuration algorithm* that selects the minimum number of active APs to satisfy the constraints in the system.

To further minimize the power consumption of APs, we introduced the *AP transmission power minimization method* in the active AP configuration algorithm [14]. This static approach estimates the minimum transmission power to achieve the required throughput using the *throughput estimation model* [15]. However, it demands numerous throughput measurements to obtain the accurate model parameters under various transmission powers.

In this paper, we present another AP transmission power minimization method using the *PI feedback control* [16], to avoid extensive measurements. The initial power is examined from the difference between the measured *received signal strength (RSS)* at the AP from the stations and the estimated RSS necessary for the target throughput. Then, the power is dynamically minimized by using the *PI feedback control*, such that the measured throughput by *iperf* [17] achieves the target one. For evaluations, we implement the proposal in the *elastic WLAN system testbed* using *Raspberry Pi* devices that have been adopted in many IoT applications, and conduct experiments with five topologies. It is proved that the approach has reduced the transmission power significantly while achieving the target throughput.

The rest of this paper is organized as follows: Section 2 reviews our previous works. Section 3 presents the transmission power minimization method using *PI feedback control* and the implementation in *elastic WLAN system* testbed. Section 4 shows evaluations of the proposal. Finally, Section 5 concludes this paper with future works.

2. Previous works

In the section, we review our previous works related to this paper.

2.1. Elastic WLAN system

Fig. 2 illustrates a topology of the *elastic WLAN system*. The server has the administrative access to all the devices on the network, and controls the system through the following three steps:

1. The server explores all the devices in the network and collects the requisite information for the active AP configuration algorithm.

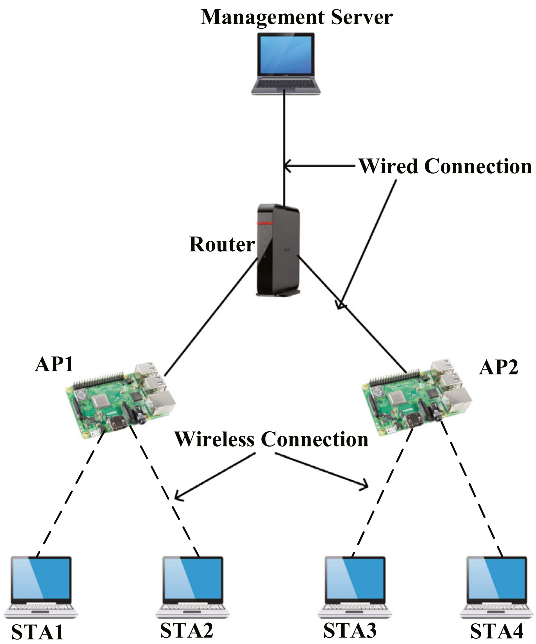


Fig. 2. Example topology of elastic WLAN system.

2. The server executes the active AP configuration algorithm and the output of the algorithm contains the list of the active APs, the station associations, and the assigned channels.
3. The server applies this output to the network by activating or deactivating the specified APs, changing the specified associations, and assigning the channels.

To evaluate the *elastic WLAN system*, we have implemented the testbed, where *Raspberry Pi* [18], is used for the AP and *Linux PC* is for the server and the station.

2.2. Throughput estimation model

In the throughput estimation model, the RSS at a station from an AP is calculated using the *log-distance path loss model*:

$$P_d = P_1 - 10\alpha \log_{10} d - \sum_k n_k W_k \tag{1}$$

where P_d represents the estimated *RSS* (dBm), P_1 does *RSS* at the 1 m distance from the AP when no obstacle exists, α does the path loss exponent, n_k does the number of $type_k$ obstacles along the path from the AP to the station, and W_k does the signal attenuation factor (dBm) for $type_k$ obstacle. Then, the throughput is calculated by using the *sigmoid function* [15] as follows:

$$Th = \frac{a}{1 + e^{-(\frac{(120+P_d)-b}{c})}} \tag{2}$$

where *Th* represents the estimated throughput (Mbps) and, *a, b*, and *c* are constant coefficients.

2.3. Static AP transmission power minimization

The AP transmission power is statically selected using the *throughput estimation model* [15] and is fixed during communications. Thus, the accuracy of the model determines the performance of this method. For the accurate model, the parameters are tuned through the two steps: (1) throughputs are measured at different station locations with various transmission powers, (2) the model parameter values are optimized by applying the *parameter optimization tool* with the throughput results. The throughput at an arbitrary transmission power is obtained by the interpolation of the estimated results at the two adjacent measured powers. Then, the least transmission power is selected to satisfy the required throughput for each AP.

2.4. Drawbacks of previous method

The previous model-based static method has two drawbacks. One drawback is the high load of throughput measurements that are required to obtain the accurate model. That is, the station and the AP must be located at different designate posi-

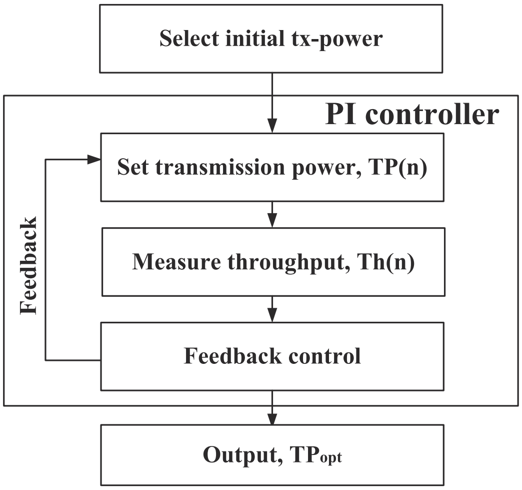


Fig. 3. Overview of AP transmission power minimization method.

tions, several transmission powers will be selected at each position, then the throughput must be measured several times for each condition of the location and the power. Nevertheless, due to frequent fluctuations of throughputs, one throughput measurement requires several minutes using *iperf* and even the measurement for a single link could take a whole day.

Another drawback is the throughput difference from the model result, due to the model accuracy and the environmental changes such as the interference from other Wi-Fi devices, the weather, and the congestion. Hence, the transmission power needs to be dynamically adjusted during communications.

2.5. Related works

In this section, we briefly introduce related works in literature to this paper.

A substantial amount of research works has been found in literature that focus on the power consumption at each active AP. For instance, Gong et al. [19] explore a genetic algorithm to control the power of each active AP in industrial wireless local area network (IWLAN).

Ref. [20] analyses the disadvantages of using the highest transmission power of the AP and explains that it can reduce the lifetime of the device, increases the interference with the nearby APs, and can reduce the performance.

Kachroo et al. [21] propose a channel assignment and transmission power control algorithm for a multi-rate WLAN. The authors consider both overlapping and non-overlapping channel assignment. In the first step, the channel is assigned to the AP while the other parameters such as the transmission power and the position are constant. Then, the second step improves the network throughput by optimizing the transmission power of the APs.

Tewari and Ghosh [22] propose a joint approach of the power tuning and the partially overlapping channel (POC) assignment. Based on the assigned POC, the algorithm performs an effective power tuning to improve the network performance.

Giovanna et al. [23] provide a heuristic approach to control the power and channel allocation process iteratively. The authors select a set of transmission power levels for the APs and the available channels in order to determine the best set-up for each AP. Then, based on the initial channel and power assignment, the algorithm tries to assign the best channel and power level by the error and trial method. This algorithm finds the best solution after a predefined number of trials so that the selected power and assigned channel can improve the overall network throughput.

3. AP transmission power minimization using PI feedback control

In the section, we propose the AP transmission power minimization method using the PI feedback control.

3.1. Overview

Fig. 3 shows the overview of the proposal, which consists of two phases. The *initial power selection* examines the initial transmission power of the AP from the difference between the measured RSS at the AP from the station and the required RSS for the target throughput estimated by the model, assuming that the RSS is proportional to the transmission power.

The *dynamic power minimization* continues changing the transmission power by the PI feedback control. The actual throughput of the link between the server and the station is measured using *iperf* periodically, assuming that the *iperf* client is installed on the station. Then, the measured throughput is used to update the power by the PI control so that it could achieve the target throughput. In the implemented testbed, the throughput measurement and the power update are applied iteratively every 20 s.

3.2. Initial power selection

The initial transmission power of the AP, $TP(0)$ (dBm), is examined through the following procedure:

1. The required RSS, $Pd(Th_{tar})$ (dBm), evaluated with the throughput estimation model to achieve the target throughput, Th_{tar} (Mbps):
$$Pd(Th_{tar}) = b - M - c \times ln\left(\frac{a}{Th_{tar}} - 1\right) \tag{3}$$
where a, b, c, and M represent the constant coefficients. In this paper, $a = 34,\ b = 57,\ c = 8,$ and $M = 120$, in [14], are adopted. This equation is derived from Eq. (2).
2. The RSS at the AP from the station, RSS_m, is measured when the maximum transmission power is used for both the AP and stations.
3. The difference between RSS_m and $Pd(Th_{tar})$, ΔPd, is calculated:
$$\Delta Pd = RSS_m - Pd(Th_{tar}) \tag{4}$$
4. The initial transmission power, $TP(0)$ (dBm), is calculated:
$$TP(0) = MaxTx - \Delta Pd \tag{5}$$
where $MaxTx$ represents the maximum transmission power of the AP. Here, $TP(0)$ must be in the feasible range:
$$TP(0) = \begin{cases} MaxTx & \text{if } TP(0) > MaxTx \\ MinTx & \text{if } TP(0) < MinTx \end{cases} \tag{6}$$
where $MinTx$ represents the minimum transmission power of the AP. In this paper, $MaxTx = 30\,\text{dBm}$ and $MinTx = 0\,\text{dBm}$ are adopted for the *Raspberry Pi* AP.

3.3. Dynamic power minimization

The transmission power of the AP, $TP(n)$ (dBm), is updated iteratively for its minimization by the *PI feedback control*:

$$TP(n) = K_P \times (Th_{tar} - Th(n)) + K_I \times \sum_{i=0}^{n} (Th_{tar} - Th(i)) \tag{7}$$

where $TP(n)$ and $Th(n)$ indicate the transmission power and the measured throughput at the nth iteration, Th_{tar} does the target throughput, and K_P and K_I do the P and I control gains, respectively. In this paper, $K_P = 0.4,$ and $K_I = 0.0015$ are adopted. In the implementation, the difference equation of the *PI control* is used:

$$TP(n) = TP(n-1) + K_P \times (Th(n-1) - Th(n)) + K_I \times (Th_{tar} - Th(n)) \tag{8}$$

3.4. Testbed implementation

The proposed method is implemented on the elastic WLAN system testbed using *Raspberry Pi* APs.

3.4.1. Initial power selection

For the initial transmission power selection, the following procedure is performed on the server:

1. The MAC and IP addresses of the AP and the associated stations are collected.
2. The AP is requested to measure the RSS from each station for 30 s at 1 s interval using the maximum transmission power (30 dBm), and send it to the server.
3. The average of the received RSS is calculated and the station (bottleneck station) with the smallest RSS will be identified.
4. The initial transmission power of the AP is calculated by the procedure in Section 3.2 using the smallest RSS.

3.4.2. Dynamic power minimization

For the dynamic transmission power minimization, the following procedure is conducted on the server:

1. The throughput to each station is measured for 20 s using *iperf*.
2. The average AP-station throughput is calculated.
3. $TP(n)$ is updated by Eq. (8).
4. $TP(n)$ is set as the transmission power of the AP.
5. Go back to 1.

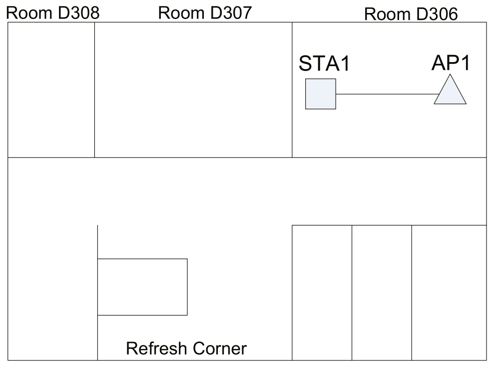


Fig. 4. *Topology 1*: one station in one room.

4. Evaluations

In this section, we evaluate the proposed transmission power minimization method through experiments using the *elastic WLAN system testbed*.

4.1. Network fields

In experiments, we consider five network topologies in two buildings in Okayama University. The two building have different structures where they were built at different years. The rooms in them are different in their sizes and are separated by different types of wall structure that has the different wall attenuation factors for the signal propagation. These two different network environments are selected to demonstrate that the proposal can be adopted in different kinds of environments and can save the power significantly.

4.2. Three methods for comparison

In evaluations, the throughput and transmission power results in three cases are compared to verify the effectiveness of the proposal, namely, *method-1: no minimization, method-2: dynamic power minimization only*, and *proposal: initial power selection and dynamic power minimization*. In *method-1)*, the transmission power is always set at the largest one (30 dBm). In *method-2)*, the power is initialized at the largest one.

4.3. Throughput constraint setup

The *minimum average station throughput threshold (G)* is basically selected in three ways so that the final transmission power will become either under saturated (=0 dBm), within the dynamic range (=0–30 dBm), or over saturated (=30 dBm). It is noted that G is selected in two ways when the power cannot be controlled within the range.

4.4. Experiments in Engineering Building-2

First, the third floor in Engineering Building-2 is adopted for *Topology 1–Topology 3*.

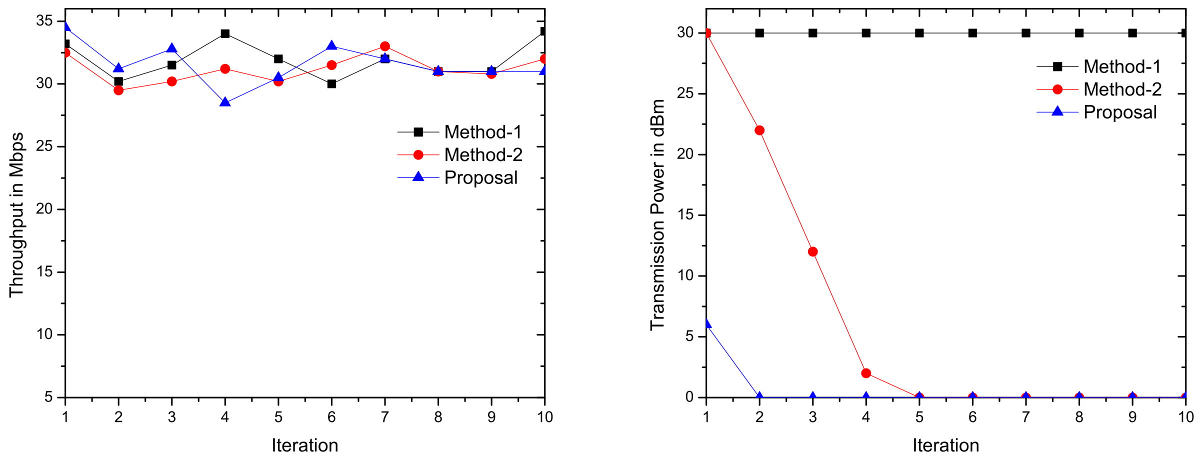
4.4.1. Topology 1: one station in same room

In *Topology 1*, one *Raspberry Pi* AP and one *Linux PC* station are allocated in the same room of the size of $7\,\mathrm{m} \times 6\,\mathrm{m}$, as shown in Fig. 4. $G = 10$ Mbps and $G = 40$ Mbps are adopted for the throughput constraint.

Figs. 5 and 6 present the changes of the throughput and transmission power results for $G = 10$ Mbps and $G = 40$ Mbps, respectively. Table 1 shows the average throughout. The experiment was executed three times and their average results were used here. For $G = 10$ Mbps, the required throughput is satisfied with the minimum transmission power (=0 dBm). However, in *method-1*, the power is fixed at 30 dBm. In *method-2*, it becomes 0 dBm at the fifth iteration. In the *proposal*, the power becomes 0 dBm at the second iteration. Thus, the *proposal* has significantly reduced the transmission power while meeting the throughput requirement. For $G = 40$ Mbps, the throughput is not satisfied even with the maximum transmission power. Thus, any method becomes the maximum power.

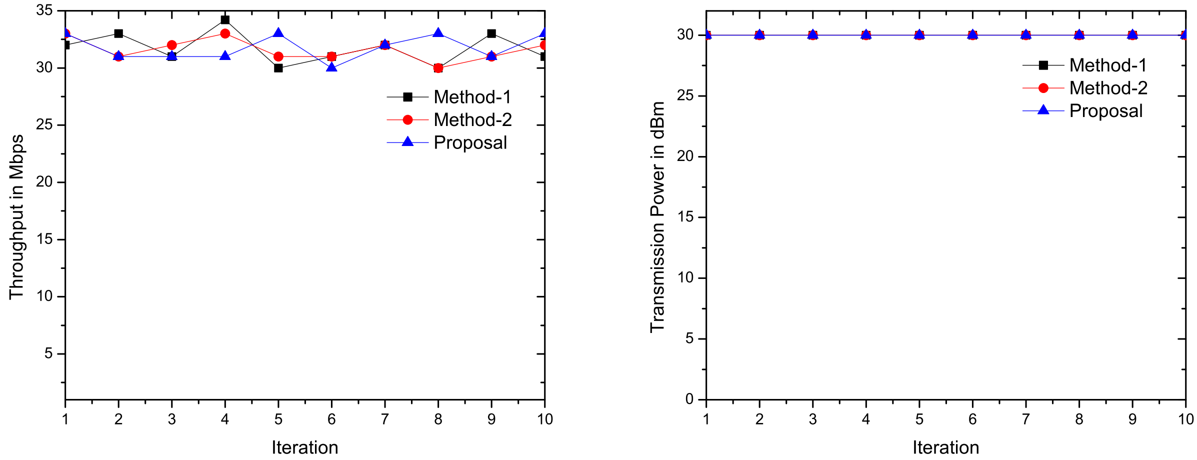
4.4.2. Topology 2: one station in corridor

In *Topology 2*, one AP is allocated in one room of size $7\,\mathrm{m} \times 6\,\mathrm{m}$ and one station is allocated in the corridor, as shown in Fig. 7. Figs. 8–10 illustrate the changes of the throughput and transmission power results for $G = 5$ Mbps, $G = 15$ Mbps, and $G = 25$ Mbps, respectively. Table 2 shows the average throughput and transmission power results.



(a) Throughput results. (b) Transmission power results.

Fig. 5. Results for *Topology 1* with $G = 10$ Mbps.



(a) Throughput results. (b) Transmission power results.

Fig. 6. Results for *Topology 1* with $G = 40$ Mbps.

Table 1
Result for *Topology 1*.

	G=10 Mbps	
Method	Avg. thr. (Mbps)	Avg. power (dBm)
Method-1	31.91	30.00
Method-2	31.19	6.60
Proposal	31.55	0.60
	G=40 Mbps	
Method-1	31.72	30.00
Method-2	31.60	30.00
Proposal	31.80	30.00

The RSS at the AP from the station is −66.10 dBm on average. Then, the *proposal* selects 19 dBm, 30 dBm, and 30 dBm as the initial power for them. The PI feedback control is applied to minimize the power to 0 dBm and 11 dBm for $G = 5$ Mbps and $G = 15$ Mbps, respectively. For $G = 30$ Mbps, the highest power (=30 dBm) is selected as the best throughput performance. Thus, the *proposal* has remarkably reduced the power while maintaining the target throughput performance.

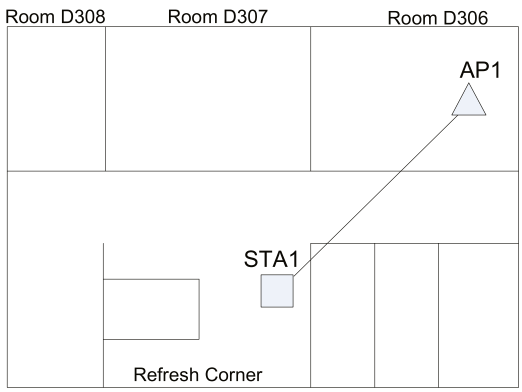


Fig. 7. *Topology 2*: one station in corridor.

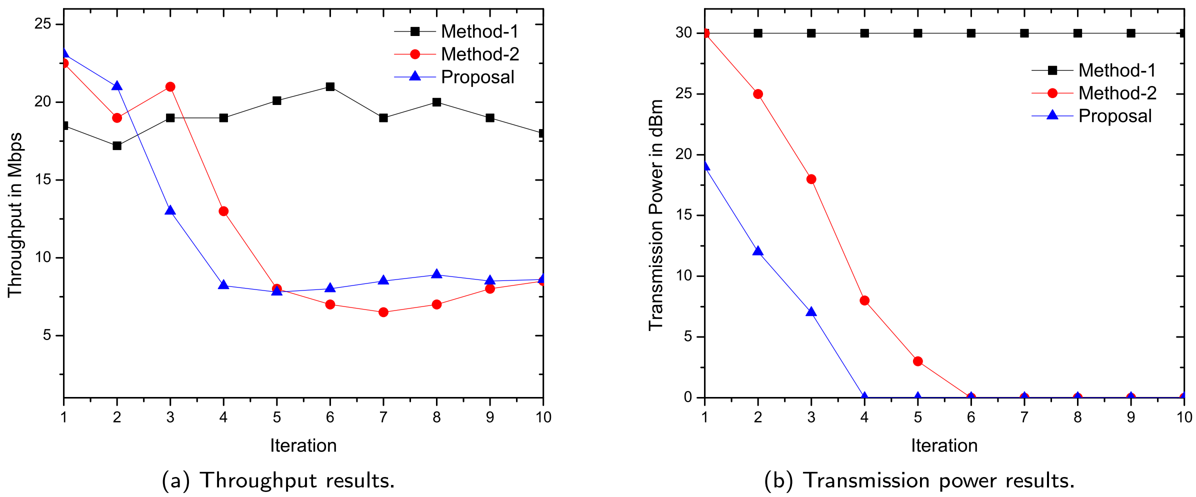


Fig. 8. Results for *Topology 2* with $G = 5$ Mbps.

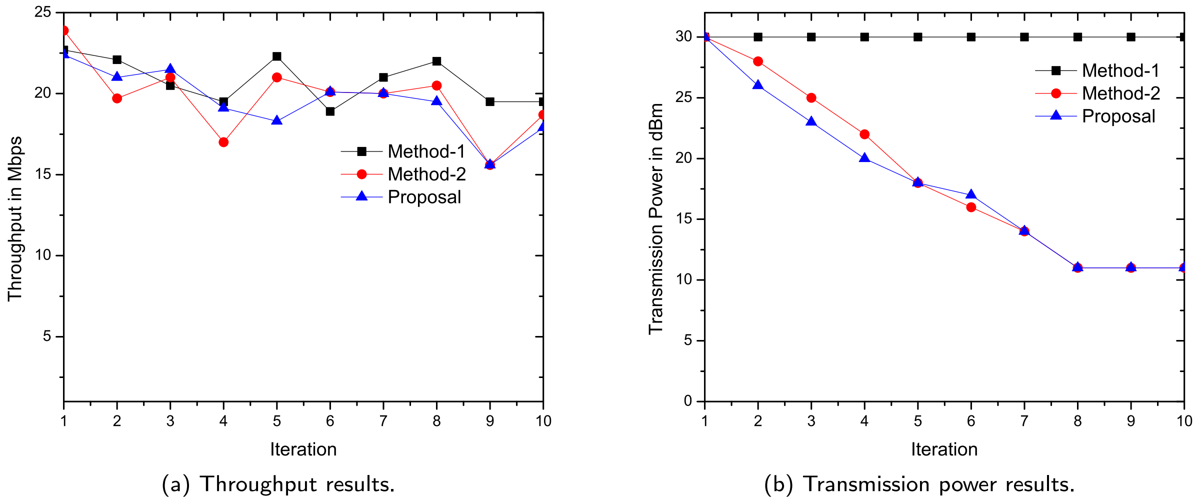
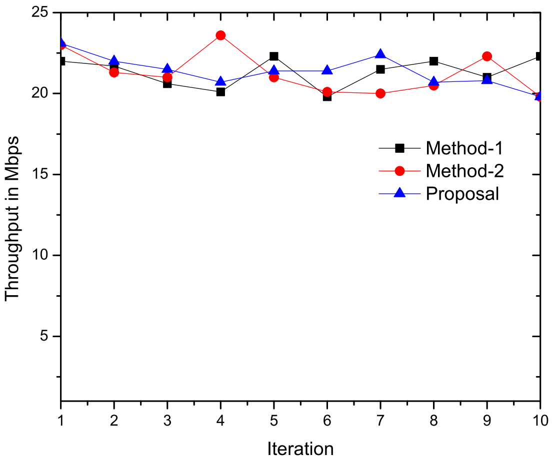
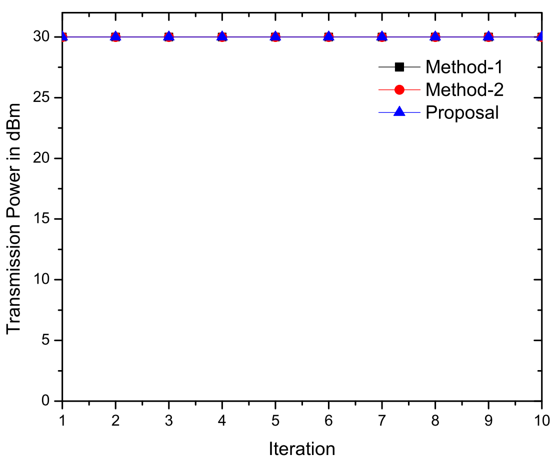


Fig. 9. Results for *Topology 2* with $G = 15$ Mbps.



(a) Throughput results.



(b) Transmission power results.

Fig. 10. Results for *Topology 2* with $G = 25$ Mbps.

Table 2
Result for *Topology 2*.

Method	Avg. thr. (Mbps)	Avg. power (dBm)
G=5 Mbps		
Method-1	19.08	30.00
Method-2	12.05	8.40
Proposal	11.56	3.80
G=15 Mbps		
Method-1	20.80	30.00
Method-2	19.75	18.60
Proposal	19.54	18.10
G=25 Mbps		
Method-1	21.33	30.00
Method-2	21.26	30.00
Proposal	21.38	30.00

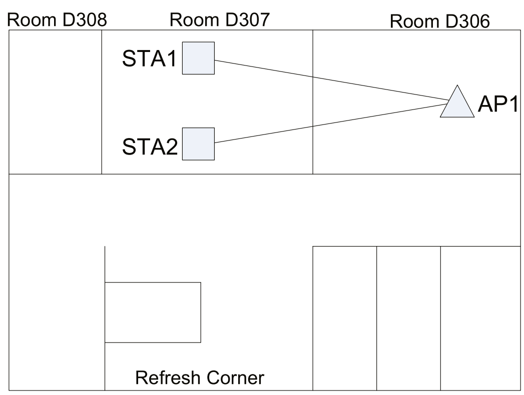
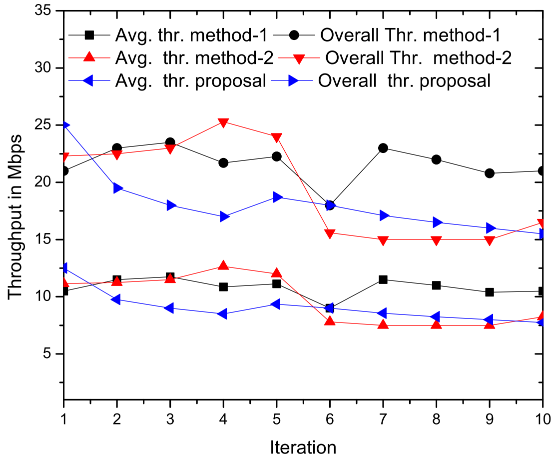


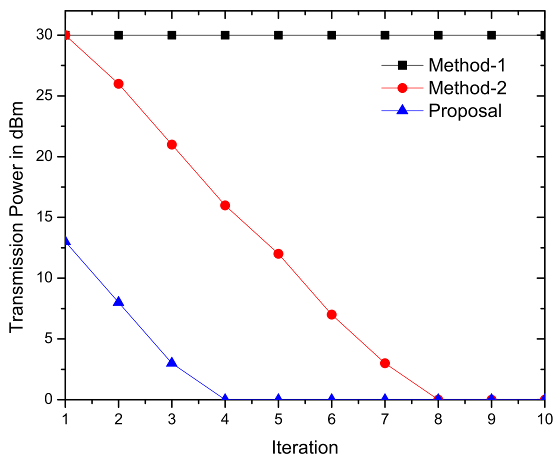
Fig. 11. *Topology 3*: two stations in different room.

4.4.3. *Topology 3: two stations in different room*

In *Topology 3*, two stations in the same room communicate with the same AP in a different room, revealed in Fig. 11. Also Figs. 12–14 demonstrate the throughput and power change results. Lastly, Table 3 provides the summary. For $G = 5$ Mbps and 10 Mbps, the *proposal* minimizes the power at the fourth or sixth iteration, respectively, where *method-2* does it at the eighth

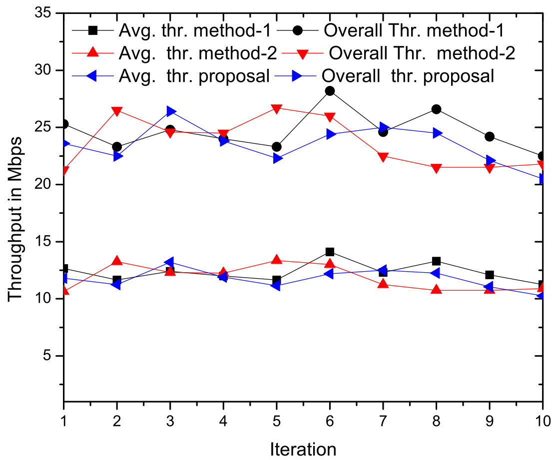


(a) Throughput results.

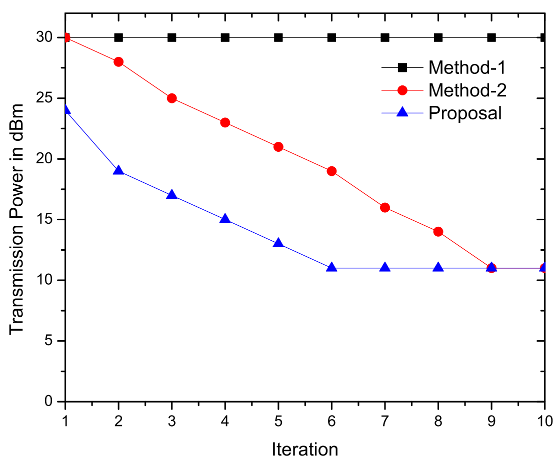


(b) Transmission power results.

Fig. 12. Results for *Topology 3* with $G = 5$ Mbps.

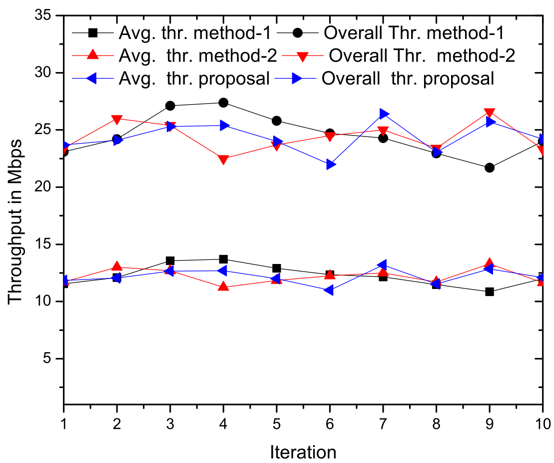


(a) Throughput results.

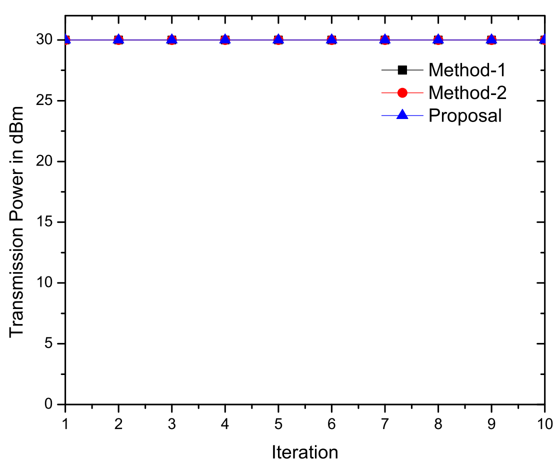


(b) Transmission power results.

Fig. 13. Results for *Topology 3* with $G = 10$ Mbps.



(a) Throughput results.



(b) Transmission power results.

Fig. 14. Results for *Topology 3* with $G = 15$ Mbps.

Table 3
Results for *Topology 3*.

	G=5 Mbps		
Method	Ave. thr. (Mbps)	Avg. total thr. (Mbps)	Avg. power (dBm)
Method-1	10.81	21.63	30.00
Method-2	9.71	19.42	11.50
Proposal	9.07	18.14	2.40
	G=10 Mbps		
Method-1	12.34	24.68	30.00
Method-2	11.85	23.69	19.80
Proposal	11.76	23.51	14.30
	G=15 Mbps		
Method-1	12.26	24.53	30.00
Method-2	12.19	24.38	30.00
Proposal	12.19	24.39	30.00

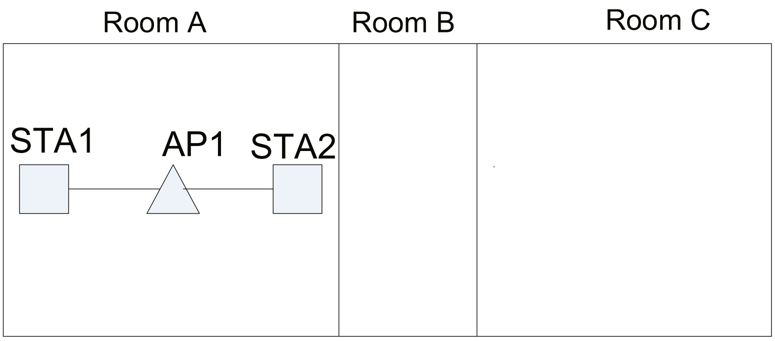


Fig. 15. *Topology 4*: two stations in same room.

Table 4
Results for *Topology 4*.

	G=10 Mbps		
Method	Ave. thr. (Mbps)	Avg. total thr. (Mbps)	Avg. power (dBm)
Method-1	16.45	32.90	30.00
Method-2	16.38	32.76	12.00
Proposal	16.33	32.66	0.50
	G=40 Mbps		
Method-1	16.34	32.67	30.00
Method-2	16.19	32.38	30.00
Proposal	16.35	32.70	30.00

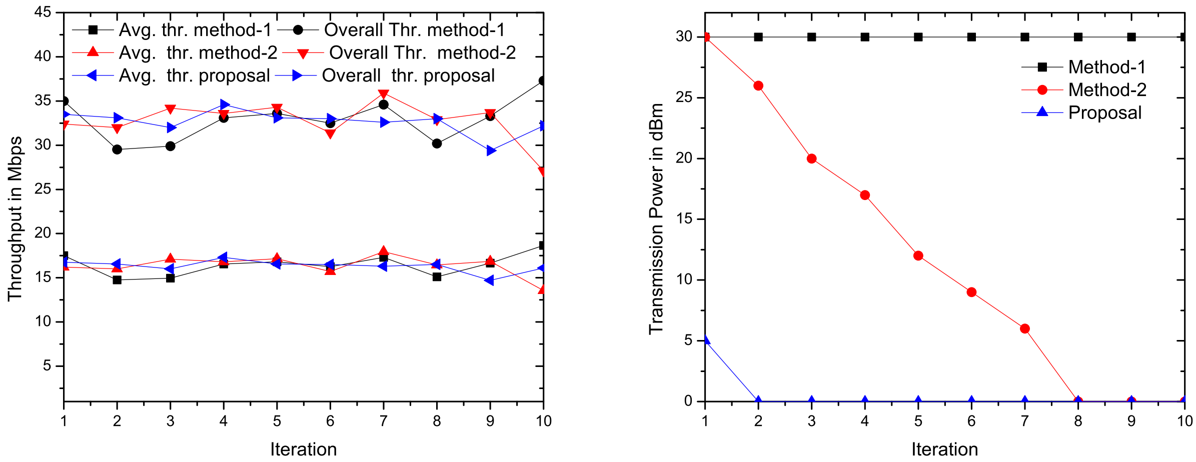
or ninth iteration. The results prove that the *proposal* has significantly reduced the transmission power while satisfying the throughput requirement.

4.5. Experiment in Graduate School Building

As the second network field, the second floor in Graduate School Building is adopted in experiments for *Topology 4* and *Topology 5*.

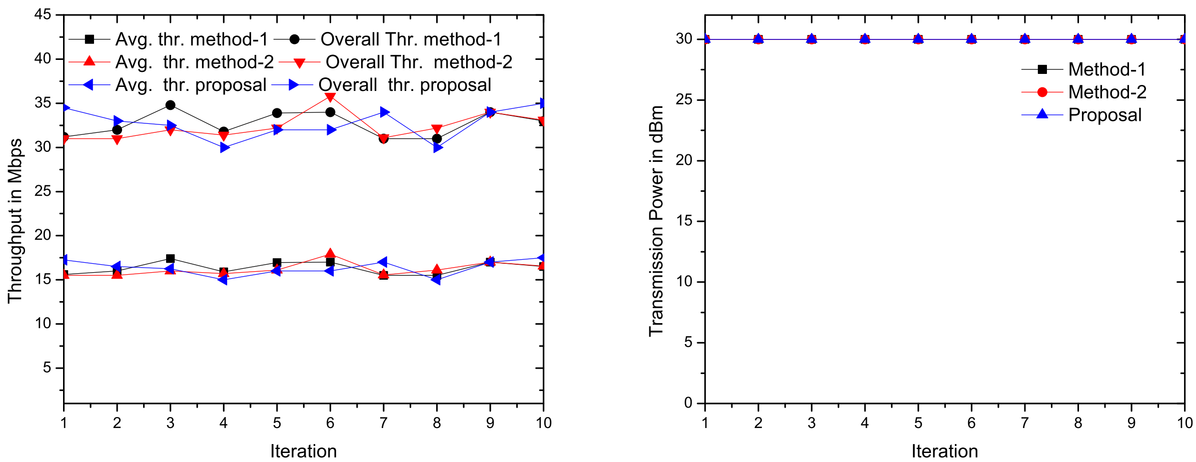
4.5.1. Topology 4: two stations in same room

In *Topology 4*, one AP and two stations are allocated in the same room of size $9\,\mathrm{m} \times 5.5\,\mathrm{m}$, shown in Fig. 15. The two stations concurrently communicate with the AP. Figs. 16 and 17 show the changes of the throughput and transmission power results for $G = 10$ Mbps and $G = 40$ Mbps, respectively, while Table 4 contains the summary results. *Method-2* minimizes the power at the eighth iteration for 10 Mbps whereas *proposal* does it at the second iteration. Once more, the approach successfully reduces the transmission power while satisfying the throughput requirement.



(a) Throughput result. (b) Transmission power results.

Fig. 16. Results for *Topology 4* with G=10 Mbps.



(a) Throughput result. (b) Transmission power results.

Fig. 17. Results for *Topology 4* with G=40 Mbps.

4.5.2. Topology 5: two stations in different room

Finally, two stations are located in a different room from the AP, as shown in Fig. 18. Figs. 19–21 present the changes of the throughput and transmission power results for $G = 3$ Mbps, $G = 10$ Mbps, and $G = 15$ Mbps, respectively. Table 5 signifies the average throughout. Again, for $G = 15$ Mbps, the power is set 30 dBm all the time. For $G = 3$ Mbps and $G = 10$ Mbps, the *proposal* minimizes the power at 0 dBm and 12 dBm, respectively, with shorter time than the *method-2*. The effectiveness of the *proposal* is confirmed then.

4.6. Overall discussions

In our current implementation, the initial transmission power is set by collecting the measured RSS at the AP from the stations. Then, the power is dynamically minimized by measuring the throughput with *iperf* using the feedback control during the communication. It is found that when the stations are located in the same room or in very near rooms as/from the AP, such as *Topology 1* and *Topology 4*, the fluctuation of RSS is small even for the minimum transmission power. Thus, in this case, the fluctuation of the transmission power may not affect the current throughput performance of the station. However, when the stations are located far from the AP, such as *Topology 2*, *Topology 3*, and *Topology 5*, the RSS will be changed significantly. Thus, in this case, a significant fluctuation in the transmission power may affect the performance of

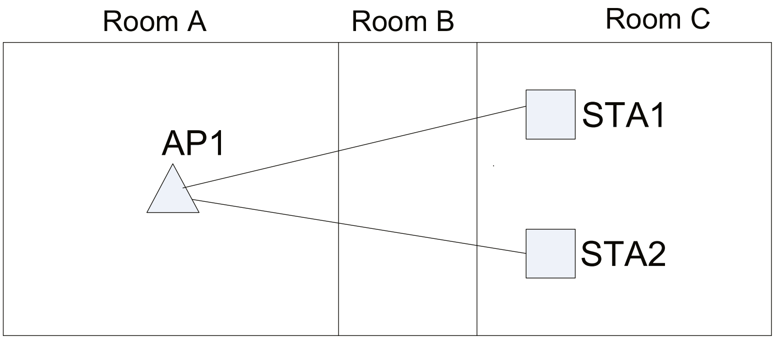
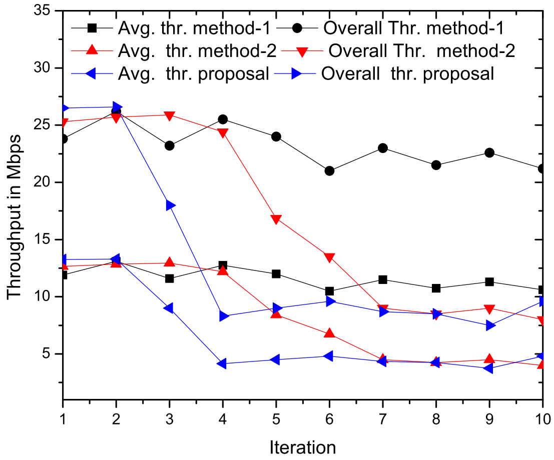
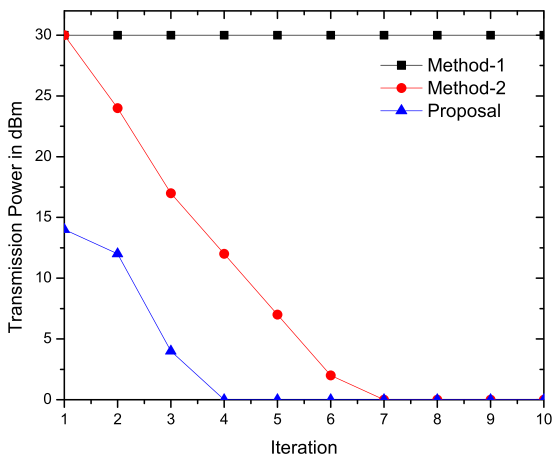


Fig. 18. *Topology 5*: two stations in different room.



(a) Throughput results.



(b) Transmission power results.

Fig. 19. Results for *Topology 5* with G=3 Mbps.

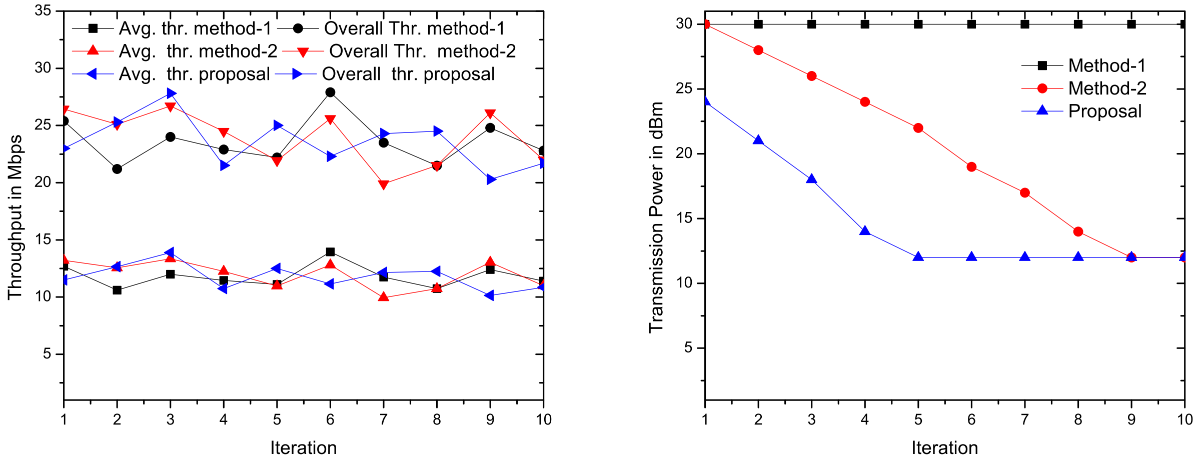
Table 5
Results for *Topology 5*.

Method	Ave. thr. (Mbps)	Avg. total thr. (Mbps)	Avg. power (dBm)
G=3 Mbps			
Method-1	11.60	23.20	30.00
Method-2	8.31	16.62	9.20
Proposal	6.62	13.24	3.00
G=10 Mbps			
Method-1	11.81	23.62	30.00
Method-2	11.99	23.98	20.40
Proposal	11.79	23.57	14.90
G=15 Mbps			
Method-1	11.92	23.85	30.00
Method-2	12.13	24.25	30.00
Proposal	12.27	24.54	30.00

our proposal. In future, we will investigate the effect of the power fluctuation to the performance and the improvement of the proposal.

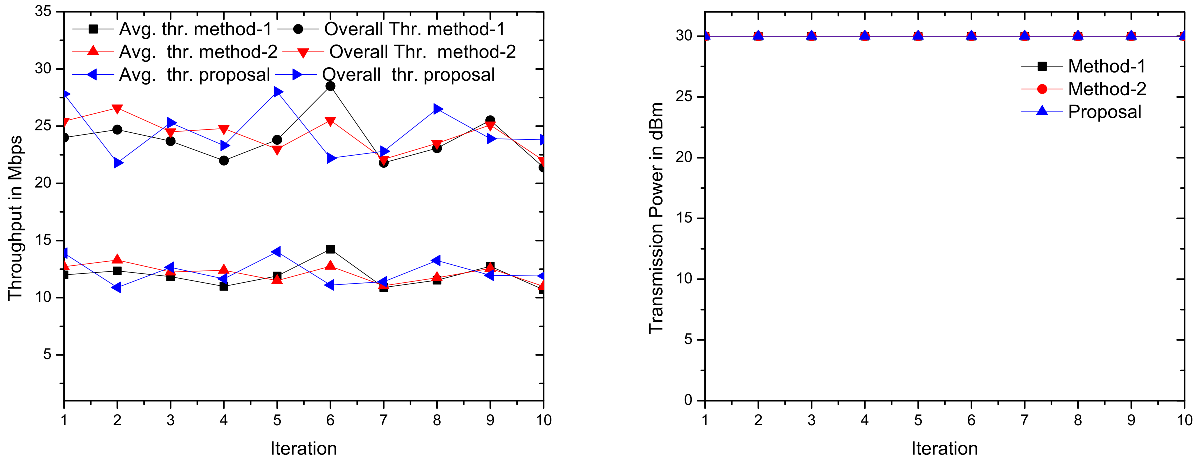
5. Conclusion

This paper proposed the *AP transmission power minimization method using PI feedback control* to reduce the power consumption of WLAN for IoT applications. The initial power is examined from the difference between the measured RSS at the AP from the station and the estimated RSS necessary for the target throughput. Then, the power is minimized by using the



(a) Throughput results. (b) Transmission power results.

Fig. 20. Results for *Topology 5* with G=10 Mbps.



(a) Throughput results. (b) Transmission power results.

Fig. 21. Results for *Topology 5* with G=15 Mbps.

PI feedback control, such that the measured throughput achieves the target one. The proposal was implemented in the *elastic WLAN system* testbed using *Raspberry Pi* devices that have been adopted in many IoT applications. The experiment results in five topologies have been validated in respect of accuracy. In future works, it will be evaluated in various network fields and topologies.

Declaration of Competing Interest

None.

Acknowledgments

This work is partially supported by JSPS KAKENHI (16K00127).

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