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Joint Optimization Method of Channel Assignment and Transmission Power for Concurrently Communicating Multiple Access-Points in Wireless Local-Area Network

Hendy Briantoro, Nobuo Funabiki, Md. Mahbubur Rahman, Kwenga Ismael Munene, Minoru Kuribayashi
Graduate School of Natural Science and Technology
Okayama University

Wen-Chung Kao
Department of Electrical Engineering
National Taiwan Normal University

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Abstract

Currently, *IEEE 802.11n wireless local-area network (WLAN)* is popular for the Internet access due to mobility, flexibility, and scalability. Multiple *access-points (APs)* are often allocated in WLAN to cover the wide area, which may cause interferences and reduce the performances. Previously, we have studied the *transmission power optimization method* for two concurrently communicating APs to reduce interferences. It selects either the maximum or minimum power for each AP such that *signal-to-noise ratio (SNR)* is highest. However, it was found that the channel assignment is also important when multiple APs are closely allocated in dense WLAN. In this paper, we propose a *joint optimization method of channel assignment and transmission power* for concurrently communicating multiple APs in WLAN. First, the same channel is assigned to the nearby APs where the *CSMA/CA protocol* works well, and the most distant channels are to the other APs. Second, the transmission power is optimized by selecting the highest measured SNR. To reduce the SNR measurement load, 1) the maximum power is assigned to every AP, 2) the initial RSS from the associated host is measured, 3) the minimum power is assigned to one AP in descending order of the initial RSS, and the SNR is measured, and 4) the power combination for the highest SNR is selected. For evaluations, we conduct extensive experiments under various network topologies using up to four *Raspberry Pi* APs. The results show that the proposal always selects the best channel and transmission power for each AP that offers the highest throughput performance.

Keywords: WLAN, access point, Raspberry Pi, channel assignment, transmission power optimization, SNR, multiple APs

1 Introduction

Currently, *IEEE 802.11n wireless local-area network (WLAN)* is popular for the Internet access due to mobility, flexibility, and scalability [1] [2]. In WLAN, the *access-point (AP)* acts as the hub to connect the wireless links and the wired ones. Since the license-free band is used in WLAN, the coverage range of one AP is limited into a small area. Therefore, multiple APs are often allocated in WLAN to cover the wide area, which may cause interferences and reduce the network performance.

In this dense WLAN, the transmission powers of the APs should be optimized to enhance the network performance, considering the capacity, the interference, and the coverage area [3] [4]. When the high transmission power is assigned, it will not only increase the capacity and the coverage area, but also increase the interference to other wireless devices. This situation may cause negative impacts to the network and degrade the performance.

The *signal-to-noise ratio (SNR)* is the common metric to measure the quality of the wireless communication. The SNR is calculated using the *receiving signal strength (RSS)* at the receiver from the transmitter and the RSS there from the interfered devices. The SNR can delineate the tradeoff of the link capacity and the interference since it compares the signal strength and the noise at the receiver [5] [6].

Previously, we have studied the *transmission power optimization method* for two concurrently communicating APs in WLAN [7]. This method selects either the maximum or minimum transmission power for each AP such that the SNR is highest among the possible ones. However, it was found that in dense WLAN where multiple APs are closely located, the optimization of the channel assignment is also critical, as well as the transmission power optimization, to maximize the network performance of WLAN.

Channel bonding (CB) is essential in IEEE 802.11n to increase the throughput performance by combining two adjacent $20MHz$ channels to become one $40MHz$ channel [8]. The number of *orthogonal channels (OCs)* in CB is only two, *channel 1+5* and *channel 9+13*, for 13 *partially overlapping channels (POCs)* at $2.4GHz$ band. When two APs are assigned different OCs, they can give the best performance.

For three or more APs, both OCs and POCs should be considered to improve the throughput performance. In [9], we have observed that when the APs are closely located, the same OC should be assigned to them, because *carrier-sense multiple access with collision avoidance (CSMA/CA)* can manage the activations of the interfered links between them properly [10] [11]. Otherwise, the different POCs with the same maximum channel interval should be assigned to the APs to reduce the interferences.

In this paper, we propose a *joint channel assignment and transmission power optimization method* for concurrently communicating multiple APs in WLAN. Firstly, we optimize the best channel of APs by assigning the most distant channels to far APs, and the same channel to nearby APs. We set the same channel to nearby APs in order to make CSMA/CA protocol well control links. Secondly, we optimize the transmission power by choosing either the maximum or minimum power for each AP such that it gives the best SNR. To reduce combinations of SNR measurements, the proposal assigns the maximum power to every AP, and measures the RSS and SNR at each AP. Then, it sequentially selects the AP to the minimum power in descending order of the initial RSS. After every AP is selected and SNR is obtained, the combination giving the largest SNR is selected as the best transmission power.

For evaluations of the proposal, we conduct extensive experiments using *Raspberry Pi* [12] for APs in various network topologies in Engineering Building #2 and Graduate School Building at Okayama University. The results show that the proposal selects the best channel and transmission power combination for the APs and improves the WLAN performance.

The framework of this paper uses the following procedures. Section 2 describes related works of this paper. Section 3 briefly discusses the IEEE 802.11 protocol. Section 4 reviews our previous studies. Section 5 presents joint channel assignment and transmission power optimization method. Sections 6 shows the evaluation results of the proposal. Finally, Section 7 presents the conclusion of this paper and the future works.

2 Related Works

In this section, we review works that related to our paper. There are several research studies discuss about joint optimization transmission power and channel assignment. However, these following works were impractical because the effectiveness is verified only in simulations. Alternatively, the effectiveness of our proposal is verified in real testbed experiments.

In [13], Tewari et al. presented a combined transmission power and POC assignment optimization to maximize the network performance in dense WLAN. Considering multiple overlapping transmissions cause a significant performance degradation due to high interference from the limited non-overlapping channels. The effectiveness was confirmed only in simulations regardless.

In [14], Garcia et al. proposed a heuristic algorithm composed of four phases to improve the network average data rate by finding the optimal channel and transmission power allocation to each AP from all the available channels and the power levels. They assumed that the *spectrum overlapping factor* is given for each channel distance or spacing between the two channels to estimate the interference between two signals, and the *signal-to-interference noise ratio (SINR)* can be calculated using this factor with the received signal powers from the APs and the received interference plus noise power. Then, the data rate or throughput is uniquely given for each SINR. These assumptions may not be correct. For example, for *Case 3* in our evaluations where three APs are located in the same room, it will give the higher throughput if the different POCs with the same maximum channel interval are assigned to them, which will give smaller interferences with smaller spectrum overlapping factors by the assumptions. However, as shown in Figures 3 and 4, our results of assigning the same POC to the two APs actually gives higher throughputs. Besides, they verified the effectiveness of their proposal in simulations using MATLAB, not in experiments using real network devices.

In [15], Zhao et al. proposed the joint transmit power control and channel allocation optimization to reduce interference and improve the throughput. First, they analyzed the correlation between transmit power and channel and formulated the interference optimization as a *mixed integer nonlinear programming (MINLP)* problem. They used *reinforcement learning (RL)* to optimize power and channel allocation and obtained the optimal joint optimization strategy through off-line training to reduce the computational complexity. And they also use the event-driven mechanism of Q-learning to decrease the complexity of online learning. However, the effectiveness was verified only in simulations.

3 Overview of IEEE 802.11 Protocol

The IEEE 802.11 WLAN standard consists of *physical-layer (PHY)* and *medium-access-channel layer (MAC)*. MAC protocol has two coordination mechanisms, they are *distributed coordination function (DCF)* and the *point coordination function (PCF)*. DCF is the essential 802.11 MAC protocol that works as a listen-before-transmit technique, according to CSMA/CA. PCF is a centralized scheduling mechanism that utilizes a point coordinator (PC) at the access point (AP) [16].

In DCF, AP always listens to the activity of the channel before transmitting the data. If it finds that the channel is continuously idle for *distributed inter-frame space duration (DIFS)*, then AP begins a *random backoff*. On the contrary, when the channel is found busy during the DIFS interval, the AP should defer its transmission until the channel is sensed idle, and then resumed. In the data frame transmission, the shortest period of time required for a wireless interface to respond the ACK frame is called *short interframe space (SIFS)*. The interval of SIFS should be enough for the physical (PHY) layer of the receiver to change its status from receiving to transmitting. SIFS should also be shorter than DIFS to send ACK frame before AP resume their backoff [17].

A *contention window (CW)* is assigned after a frame is transmitted for collision avoidance. The window states the contention time of various APs who contend with each other for access to the channel. When AP goes into the backoff state, it randomly selects the number of time slots, the random number must be greater than 0 and smaller than a maximum of CW. When the transmission is successful, CW will be reset to the minimum CW size. However, if the data is still unsuccessful to transmit, the CW is increased by two with each unsuccessful transmission until it reaches its maximum value [18].

4 Review of Previous Works

In this segment, we review previous works on the transmission power optimization method for concurrently communicating two APs in WLAN.

Our prior works consider that two APs, called *AP1* and *AP2*, are allocated in WLAN, where *AP1* is associated with multiple hosts, $H1_i$ for i=1,. . . , $n1$, and *AP2* is associated with multiple hosts, $H2_i$ for i=1,. . . , $n2$. The proposed method selects either the minimum or maximum transmission power for *AP1* and *AP2*, such that the power combination gives the largest SNR among the four combinations. The subsequent procedure describes the details of the method:

1. Assign the transmission power for each AP by selecting one of the four combinations one by one:
   - $P_{AP1} = P_{min}$ and $P_{AP2} = P_{min}$.
   - $P_{AP1} = P_{min}$ and $P_{AP2} = P_{max}$.
   - $P_{AP1} = P_{max}$ and $P_{AP2} = P_{min}$.
   - $P_{AP1} = P_{max}$ and $P_{AP2} = P_{max}$.

   where P_{AP1} and P_{AP2} represent the transmission power of *AP1* and *AP2* respectively, and $P_{min} = 0dBm$ and $P_{max} = 20dBm$ are used for *Raspberry Pi 3 B+* [12] with *TP-Link TL-WN722N wireless NIC adapter* [19].

2. Measure the following RSS for each combination:
   - $RSS_{H1_i,AP1}$: RSS at *AP1* of the signal from $H1_i$
   - $RSS_{H2_j,AP1}$: RSS at *AP1* of the signal from $H2_j$
   - $RSS_{H1_i,AP2}$: RSS at *AP2* of the signal from $H1_i$
   - $RSS_{H2_j,AP2}$: RSS at *AP2* of the signal from $H2_j$
   - $RSS_{APx_k,AP2}$: RSS at *AP2* of the signal from an outside AP
   - $RSS_{APx_k,AP1}$: RSS at *AP1* of the signal from an outside AP.

   $RSS_{H1_i,AP1}$ and $RSS_{H2_j,AP2}$ represent the signal strength to transmit data, and the others become noises to them. It is noted that the *outside AP* indicates the AP that cannot be controlled by the proposed method.

3. Calculate SNR of *AP1* by Eq. (1).

$$SNR_{AP1} = \frac{\frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP1})}{(\frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP2}) + \frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP1}) + RSS_{AP2,AP1} + \frac{1}{p}\sum_{k=1}^{p}(RSS_{APx_k,AP1}))} \tag{1}$$

4. Calculate SNR of *AP2* by Eq. (2).

$$SNR_{AP2} = \frac{\frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP2})}{(\frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP1}) + \frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP2}) + RSS_{AP1,AP2} + \frac{1}{p}\sum_{k=1}^{p}(RSS_{APx_k,AP2}))} \tag{2}$$

5. Calculate the average SNR by Eq. (3).

$$aveSNR = \frac{1}{2}(SNR_{AP1} + SNR_{AP2}) \tag{3}$$

6. Select the combination that has the largest $aveSNR$ after applying all combinations, and assign the corresponding powers, P_{AP1} and P_{AP2}, to the APs.

5 Joint Channel Assignment and Transmission Power Optimization Method

The proposed algorithm is a joint algorithm of both the channel assignment optimization and the transmission power optimization. In this paper, to simplify the algorithm procedure and reduce the execution cost, we first assign the channels to the APs and then, fix them while optimizing the transmission powers. It can avoid the increasing number of steps to measure the RSS by considering more number of combinations of channels and powers, which may make the algorithm infeasible.

5.1 Channel Assignment Optimization Method

We explain the channel assignment optimization method in this section.

5.1.1 Idea

To enhance the throughput performance of the WLAN, we assume the adoption of the *channel bonding (CB)*. Then, *channel 1+5* and *channel 9+13* become the *orthogonal channels (OCs)* when 13 *partially overlapping channels (POCs)* are available.

5.1.2 Procedure

In the channel assignment, when the WLAN has two APs, the two different OCs are assigned them. When the WLAN has three or more APs, both OCs and POCs are considered. For the APs that are closely located, the same OC is assigned to them so that the CSMA protocol performs properly. For the other APs, the different POCs with the same maximum channel interval are assigned to reduce the interferences among them.

1. Assign the different POCs with the same maximum channel interval to the APs.
2. Assign the maximum transmission power for each AP.
3. Measure RSS at AP_p from AP_q, RSS_{AP_p,AP_q}, for $p \neq q$.
4. Sort the RSS_{AP_p,AP_q} in descending order.
    (a) Select two APs that have the highest RSS_{AP_p,AP_q} where at least one AP is not assigned a channel.
    (b) If $RSS_{AP_p,AP_q} > RSS_{AP_{threshold}}$, assign the same OC to them.
5. Assign the different POCs from the assigned OCs with the same maximum channel interval to the remaining APs if they exist.
6. If one OC is not assigned to any AP, assign it to the last AP that was assigned another OC.

The threshold $RSS_{AP_{threshold}}$ should be properly given to detect the closely located APs. In this paper, $RSS_{AP_{threshold}} = -60dBm$ is adopted and selected by extensive experiments.

5.2 Transmission Power Optimization Method

In this section, we present the transmission power optimization method for each AP in WLAN.

5.2.1 Idea

To begin with, reducing the SNR measurements is the important objective in this method. The preceding study needs measurement for each possible combination of the assigned powers to the APs. When the number of APs is limited to two, the number of combinations is only four. Accordingly, if the number of APs is N, measurements will be 2^N, meaning that this is ineffective for large N.

In this paper, the proposed method selects only the minimum transmission power or the maximum transmission power of the device for any AP. This comes from the results of our previous study in [20] on how the overall throughput performance of the WLAN is effected when the transmission power of each AP is gradually increased from the minimum to the maximum in various topologies. Here, it was shown that the overall throughput performance of the WLAN is maximized when either the maximum power or the minimum power is assigned at each AP in any topology.

SNR is the metric to measure the quality of the wireless communication. SNR can describe the link capacity and the interference at the same time by comparing the received signal strength and the noise level. SNR can be calculated by the *receiving signal strength (RSS)* at the receiver from the targeted device and interfered devices. The higher SNR indicates the higher throughput performance of WLAN as reported in [5][6].

In general, the maximum transmission power of an AP provides the highest throughput for the associated link when no interfered link exists. However, when multiple links exist in the same field and can be interfered with each other, the maximum transmission power also maximizes the interferences to the adjacent links, and can decrease the overall throughput of the WLAN, because of the throughput drops of the links due to the interferences.

It has been observed that when the link distance between the AP and the host is sufficiently small, even the minimum transmission power of the AP gives the same highest throughput to the link as the maximum transmission power, because both power cases adopt the same fastest modulation coding scheme (MCS). From these observations, we focus on the SNR to select the best combination of the transmission powers and the channels. The devices adopted in this paper use the *single input single output (SISO)* technology.

This proposed method will give the answer to the weakness of the earlier method. It can reduce the number of SNR measurements to at most N. The maximum transmission power of an AP provides the highest throughput for the associated link. Nevertheless, it can increase the interference to other neighbor links, and may decrease the overall throughput of the network. Besides, when the distance between AP and host is short, even the minimum power of the AP will not decrease the throughput due to the non-linear feature of the throughput performance [21].

Thus, the power of the AP should be changed to the minimum from the maximum, if only the associated host is adequately adjacent from it. Because it is impossible to select which APs should be changed, we take the linear search approach of selecting a promising AP one by one after initially assigning the maximum transmission power to every AP.

In this paper, we use *Raspberry Pi 3 B+* with *TP-Link TL-WN722n wireless NIC adapter* for the APs by running *hostapd* on the device. The maximum transmission power of this device is $20dBm$ and the minimum value is $0dBm$. These are the maximum and minimum transmission power values we have adopted in our proposed method.

5.2.2 Procedure

The following procedure describes the proposed AP transmission power optimization method.

1. Assign the maximum transmission power for each AP.

2. Measure the *RSS* at each AP from the associated hosts and the *SNR* considering any interfering AP and host. The *SNR* for AP_p in the WLAN is calculated by Eq. (4).

$$SNR_{AP_p} = \frac{\frac{1}{n_p}\sum_{i=1}^{n_p}(RSS_{H_{p,i},AP_p})}{\sum_{\substack{q=1\\q\neq p}}^{m} RSS_{AP_q,AP_p} + \sum_{\substack{q=1\\q\neq p}}^{m}\frac{1}{n_q}\sum_{i=1}^{n_q} RSS_{H_{q,i},AP_p} + \sum_{\substack{q=1\\q\neq p}}^{m}\frac{1}{n_p}\sum_{i=1}^{n_p} RSS_{H_{p,i},AP_q} + \sum_{x\in IAP_{AP_p}} RSS_{AP_x,AP_p}} \tag{4}$$

   n_p represents the number of hosts associated with AP_p, $H_{p,i}$ does the i-th associated host, $RSS_{H_{p,i},AP_p}$ does the RSS at AP_p from $H_{p,i}$, IAP_{AP_p} does the set of unknown APs that are interfered with AP_p.

3. Calculate the average SNR for all the APs by Eq. (5).

$$aveSNR = \frac{1}{m}\sum_{p=1}^{m}(SNR_{AP_p}) \tag{5}$$

4. Sort the APs in descending order of *RSS* and make the sorted list of the APs.

5. Select the first AP in the list and assign the minimum power to the AP.

6. Measure the *RSS* and calculate *SNR* at every AP.

7. Calculate the average SNR for all the APs.

8. If the average SNR becomes smaller than the previous one, select the previous combination of transmission powers to the APs and terminate the procedure.

9. Remove the selected AP from the sorted list and go to 5.

   For the *Raspberry Pi* AP, the RSS can be measured by executing the *iw command*. Since the measured RSS tends to fluctuate, RSS is measured at 30 times with the one second interval, and their average value is used. By running this command, it can show all RSS from devices. By checking the MAC Address, we can classify which is the received signal or interfering signal.

6 Evaluations

In this section, we evaluate the proposal with various network topologies using *Raspberry Pi* for APs. For evaluation, the hosts are not moved in each topology. For a static state of non-moving hosts, the proposal measures the required RSS, assigns the channels to the APs, calculates the SNR, and assigns the transmission powers to the APs. In each static host state, this procedure should be applied once.

When hosts are moved, the RSS and SNR will be changed, such that the best assignment of the channels and transmission powers to the APs may be different from the previous one. To deal with such dynamic host movement states, a simple way is to apply the proposal every time a host is moved.

However, it takes the costs of measuring the RSS while changing the transmission powers of the APs. If the best assignment is different from the previous one, the new channels and transmission powers need to be assigned to the APs while keeping the communications between the hosts and the APs. These will be obstacles of the proposed algorithm in dynamic host movement states.

Therefore, further investigation on how the assignment update is processed while keeping the communications, the performance improvement by the new assignment, and the limitations of the dynamic approach will be studied in the future works.

6.1 Comparison Methods

In the evaluations, the following three methods are considered for performance evaluations of the proposal through comparisons:

1. The first method assigns the different POCs with the same maximum channel interval and the maximum transmission power to the APs.

2. The second method assigns the different POCs with the same maximum channel interval to the APs and optimizes the transmission power by the proposal.

3. The third method optimizes the channel assignment by the proposal and assigns the maximum transmission power to the APs.

6.2 Experiment Setup

In the experiments, we use *Raspberry Pi 3 B+* [12] with *TP-Link TL-WN722N wireless NIC adapter* [19] for APs by running *hostapd* [22], and *Fujitsu* and *Toshiba* laptop PCs for servers and hosts. We use the CB at $2.4GHz$. For measuring the throughput, *iperf 2.0.5 software* [23] is used by generating TCP traffics with the $477KB$ TCP window and the $8KB$ buffer. At the same time, the RSS is measured by *iw commands*. Table 1 displays the details of devices and software in the experiments. We assign the *CB* channel at *Raspberry Pi 3 B+* by using the following Linux commands:

```
ieee80211n=1
channel=1
ht_capab=[HT40+][SHORT-GI-20][SHORT-GI-40][DSSS_CCK-40][MAX-AMSDU-3839]
```

Table 1: Device and software specifications.

access point	
model	Raspberry Pi 3 B+
CPU	Broadcom BCM2837B0 @1.4Ghz
RAM	1GB LPDDR2 SDRAM
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd
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

Here, we measure the throughput by generating downlink TCP traffics from the AP (server) to the host using *iperf* software. Downlink TCP traffics are common since users often download data from servers to hosts using TCP at Web site accesses. Jeong et al. in [24], and Kim et al. in [25] showed that the traffics in most wireless multimedia applications are not symmetric toward downlinks (from APs to hosts), compared to uplinks (from hosts to APs). Large files will sometimes be transmitted at downlinks, where very short commands *(bytes)* are transmitted at uplinks. Thus, they claimed that downlinks should be allocated more bandwidth than uplinks.

Figure 1 shows the testbed system. This server dynamically collects the information of the associated hosts from every AP and the RSS. Then, when it finds a new host, it optimizes the channel assignments and the transmission powers of the APs by running the proposed algorithm.

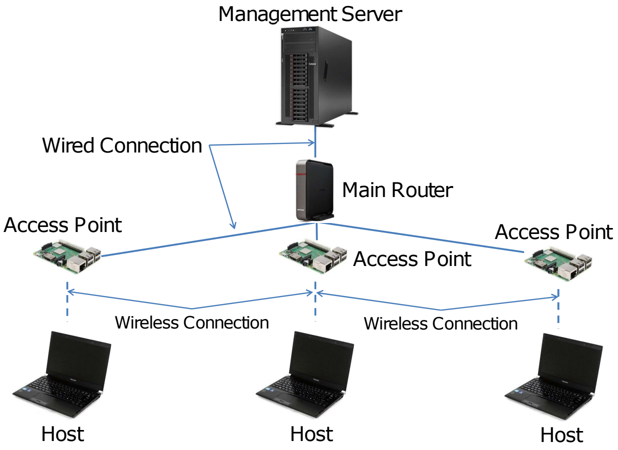


Figure 1: Testbed system.

6.3 Evaluation Scenarios

We evaluate the proposed method under various scenarios for different network conditions. Here, we consider the different conditions in the following terms:

(1) the building,

(2) the number of APs and hosts,

(3) the located rooms of APs, and

(4) the distances between APs and hosts.

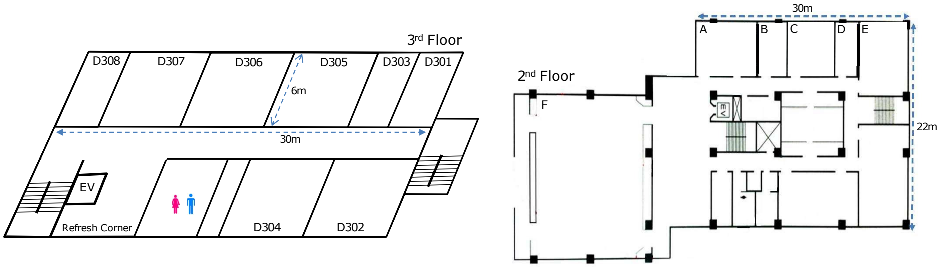
For (1), two buildings in Okayama University, *Engineering Building #2* and *Graduate School Building*, are used for the network field. The results in *Engineering Building #2* are presented and discussed in Section 6.4. The results in *Graduate School Building* are presented and discussed in Section 6.5.

For (2), *two*, *three*, and *four* are investigated for the number of APs and hosts in the network. The network with *two* APs/hosts are investigated in *Case 1* - *Case 2* in both buildings. The network with *three* APs/hosts are investigated in *Case 3* - *Case 5* in both buildings. The network with *four* APs/hosts are investigated in *Case 6* - *Case 9* in both buildings.

For (3), the strongly interfered condition where all the APs are located in the same room, the medium interfered condition where a subset of the APs are located in the same room, and the less interfered condition where all the APs are located in different rooms, are considered. The strongly interfered condition is considered in *Case 1*, *Case 3*, and *Case 6*. The medium interfered condition is considered in *Case 4*, *Case 7*, and *Case 8*. The less interfered condition is considered in *Case 2*, *Case 5*, and *Case 9*.

For (4), the strong receiving signal condition where the AP and the host are located in the same room with $1m$ distance, and the weak receiving signal condition where the AP and the host are located in different rooms with $8m$ distance, are considered. The strong receiving signal condition is considered in *Case 1*, *Case 3*, *Case 4*, *Case 6*, *Case 7*, and *Case 8*. The weak receiving signal condition is considered in *Case 2*, *Case 5*, and *Case 9*. In these three cases, we consider it is natural, even if the hosts can be located in different rooms from the APs, because the APs are located in different rooms. In other cases, some APs are located in the same room. Thus, the hosts should be located in the same rooms as the APs.

Figure 2 shows the fields in this paper. Table 2 and 3 show experiment cases in Engineering Building #2 and Graduate School Building, respectively.



Engineering Building #2   Graduate School Building

Figure 2: Experiment fields.

Table 2: Experiment cases in Engineering Building #2.

Case	Number of APs	Scenario	AP1 Location	H1 Location	AP2 Location	H2 Location	AP3 Location	H3 Location	AP4 Location	H4 Location
1	2	All APs are in one room	D307	D307	D307	D307	-	-	-	-
2	2	All APs ares in different room	D307	D306	In front of D301	In front of D303	-	-	-	-
3	3	All APs are in one room	D307	D307	D307	D307	D307	D307	-	-
4	3	Two APs are in one room	D307	D307	D307	D307	D306	D306	-	-
5	3	All APs are in different rooms	D307	D306	In front of D308	In front of D308	In front of D301	In front of D306	-	-
6	4	All APs are in one room	D306	D306	D306	D306	D306	D306	D306	D306
7	4	Three APs are in one room	D306	D306	D306	D306	D306	D306	D307	D307
8	4	Two APs are in one room	D306	D306	D306	D306	D307	D307	D307	D307
9	4	All APs are in different rooms	D307	D308	In front of D308	In front of D306	In front of D301	D306	Refresh Corner	Refresh Corner

Table 3: Experiment cases in Graduate School Building.

Case	Number of APs	Scenario	AP1 Location	H1 Location	AP2 Location	H2 Location	AP3 Location	H3 Location	AP4 Location	H4 Location
1	2	All APs are in one room	A	A	A	B	-	-	-	-
2	2	All APs ares in different room	A	B	C	D	-	-	-	-
3	3	All APs are in one room	F	F	F	F	F	F	-	-
4	3	Two APs are in one room	A	A	A	A	C	C	-	-
5	3	All APs are in different rooms	A	B	C	D	E	In front of D	-	-
6	4	All APs are in one room	F	F	F	F	F	F	F	F
7	4	Three APs are in one room	F	F	F	F	F	F	In front F	In front A
8	4	Two APs are in one room	A	A	A	B	C	C	C	D
9	4	All APs are in different rooms	A	B	C	D	E	In front of D	In front of F	In front of F

6.4 Evaluation Results in Engineering Building #2

Figure 3 shows the experiment results in Engineering Building #2. It indicates that the proposal always selects the best channel and transmission power for every AP that gives the higher throughput than any comparison method. For references, Table 4 shows the RSS between APs and Table 5 shows the assigned channel and transmission power to each AP by the proposal.

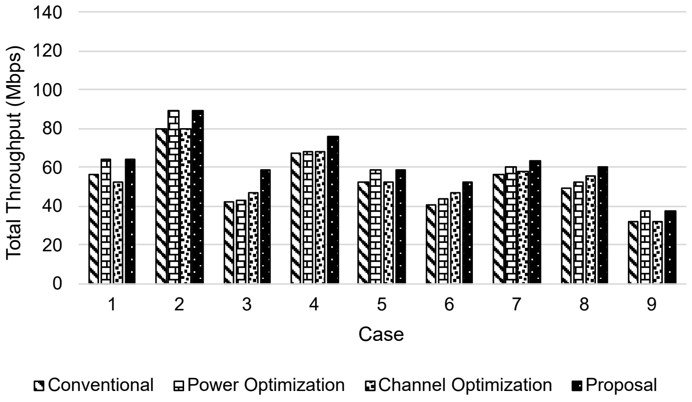


Figure 3: Results in Engineering Building #2.

Table 4: Measured RSS between APs in Engineering Building #2.

Case	$RSS_{AP1,AP2}$ (dBm)	$RSS_{AP1,AP3}$ (dBm)	$RSS_{AP2,AP3}$ (dBm)	$RSS_{AP1,AP4}$ (dBm)	$RSS_{AP2,AP4}$ (dBm)	$RSS_{AP3,AP4}$ (dBm)
1	-33.18	-	-	-	-	-
2	-79.02	-	-	-	-	-
3	-30.93	-39.06	-31.13	-	-	-
4	-30.86	-59.57	-54.48	-	-	-
5	-62.98	-79.37	-74.55	-	-	-
6	-33.08	-33.24	-39.27	-38.96	-32.89	-33.19
7	-33.06	-33.31	-39.41	-56.32	-54.83	-53.43
8	-33.11	-53.74	-55.67	-56.13	-54.71	-33.34
9	-62.77	-79.37	-74.23	-74.64	-61.05	-76.51

Table 5: Channel and transmission power assignment results in Engineering Building #2.

Case	Optimized channel				Optimized transmission power			
	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
1	1+5	9+13	-	-	min.	min.	-	-
2	1+5	9+13	-	-	max.	min.	-	-
3	1+5	1+5	9+13	-	min.	min.	min.	-
4	1+5	1+5	9+13	-	min.	min.	min.	-
5	5+9	1+5	9+13	-	max.	min.	max.	-
6	1+5	1+5	1+5	9+13	min.	min.	min.	min.
7	1+5	1+5	1+5	9+13	min.	min.	min.	min.
8	1+5	1+5	9+13	9+13	min.	min.	min.	min.
9	1+5	9+13	4+8	7+11	max.	max.	max.	min.

6.4.1 Case 1

Two APs and two hosts are in the same room that has $7m \times 6m$ size. Thus, two different OCs are assigned to the APs. Besides, the minimum transmission power is assigned to each AP since the host is located near the AP.

6.4.2 Case 2

Two APs are located at distance places. Two different OCs are assigned to them. The maximum transmission power is assigned to *AP1* since *H1* is far from it. The minimum power is assigned to *AP2* since *H2* is near it.

6.4.3 Case 3

Three APs and three hosts are located in the same room. The same OC is assigned to *AP1* and *AP2*, because the RSS between them is $-30.93dBm$ that is larger than the threshold $-60dBm$. Another OC is assigned to *AP3* to reduce the interferences from the other APs. Then, the minimum transmission power is assigned to every AP since any host is located near the AP.

6.4.4 Case 4

Two APs are located in the same room, and another AP is in a different room. Thus, the same OC is assigned to *AP1* and *AP2*, and another OC is assigned to *AP3*. The minimum transmission power is assigned to every AP since any host is located near the AP.

6.4.5 Case 5

Three APs are located in different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1* and *AP3*, since the associated host is far from the AP. The minimum power is assigned to *AP2* since the associated host is near it.

6.4.6 Case 6

Four APs and four hosts are placed in the same room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4* to reduce the interferences from the other APs. The minimum transmission power is assigned to every AP since any host is near the AP.

6.4.7 Case 7

Three APs are located in the same room and another AP is in a different room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4*. The minimum transmission power is assigned to each AP since any host is near the AP.

6.4.8 Case 8

Two APs are positioned in the same room. The same OC is assigned to *AP1* and *AP2*. Another OC is assigned to *AP3* and *AP4*. The minimum transmission power is assigned to each AP because any host is near the AP.

6.4.9 Case 9

Four APs are located in different rooms. The RSS between them is smaller than the threshold. Thus, the four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1*, *AP2*, and *AP3*, since the associated host is far from the AP. The minimum power is assigned to *AP4* since the associated host is near it.

6.5 Evaluation Results in Graduate School Building

Figure 4 shows the experiment results in Graduate School Building. Again, the proposal gives the highest throughput for any case. Table 6 shows the RSS between the APs, and Table 7 shows the assigned channel and transmission power to each AP by the proposal.

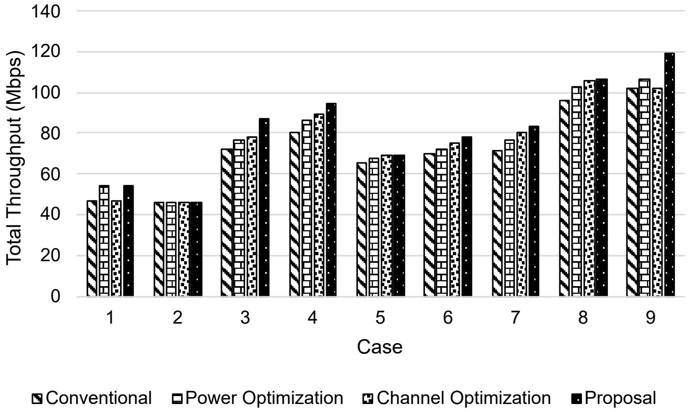


Figure 4: Results in Graduate School Building.

Table 6: Measured RSS between APs in Graduate School Building.

Case	$RSS_{AP1,AP2}$ (dBm)	$RSS_{AP1,AP3}$ (dBm)	$RSS_{AP2,AP3}$ (dBm)	$RSS_{AP1,AP4}$ (dBm)	$RSS_{AP2,AP4}$ (dBm)	$RSS_{AP3,AP4}$ (dBm)
1	-33.56	-	-	-	-	-
2	-74.54	-	-	-	-	-
3	-46.18	-52.11	-46.23	-	-	-
4	-46.34	-79.31	-70.42	-	-	-
5	-74.16	-79.44	-76.21	-	-	-
6	-44.16	-43.73	-50.39	-50.81	-43.92	-44.45
7	-44.11	-43.69	-50.42	-69.61	-68.38	-66.75
8	-35.24	-56.52	-57.21	-58.98	-56.53	-35.81
9	-74.77	-79.65	-76.33	-64.59	-78.12	-89.73

Table 7: Channel and transmission power assignment results in Graduate School Building.

Case	Optimized channel				Optimized transmission power			
	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
1	1+5	9+13	-	-	min.	max.	-	-
2	1+5	9+13	-	-	max.	max.	-	-
3	1+5	1+5	9+13	-	min.	min.	min.	-
4	1+5	1+5	9+13	-	min.	min.	min.	-
5	5+9	1+5	9+13	-	max.	max.	max.	-
6	1+5	1+5	1+5	9+13	min.	min.	min.	min.
7	1+5	1+5	1+5	9+13	min.	min.	min.	max.
8	1+5	1+5	9+13	9+13	min.	max.	min.	max.
9	1+5	4+8	7+11	9+13	max.	max.	max.	min.

6.5.1 Case 1

Two APs are positioned in the same room. Two different OCs are assigned to them. The minimum transmission power is assigned to *AP1* because *H1* is near it. The maximum power is assigned to *AP2* since *H2* is in a different room.

6.5.2 Case 2

Two APs are located in different rooms. Two different OCs are assigned to them. The maximum transmission power is assigned to *AP1* and *AP2* since any host is located in a different room.

6.5.3 Case 3

Three APs and three hosts are placed in a big room. The same OC is assigned to *AP1* and *AP2*, because the RSS between them is larger than the threshold $-60dBm$. Another OC is assigned to *AP3*. Then, the minimum transmission power is assigned to each AP since any host is near the AP.

6.5.4 Case 4

Two APs are located in the same room and another AP is in a different room. The same OC is assigned to *AP1* and *AP2*, and another OC is assigned to *AP3*. The minimum transmission power is assigned to each AP because any host is near the AP.

6.5.5 Case 5

Three APs are located in different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to each AP since any associated host is located in a different room from the AP.

6.5.6 Case 6

Four APs and four hosts are placed in the same room. The same OC is assigned to *AP1*, *AP2*, and *AP3*, another OC is assigned to *AP4*. The minimum transmission power is assigned to every AP since any host is near the AP.

6.5.7 Case 7

Three APs are located in the same room and another AP is in a different room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4*. The minimum transmission power is assigned to *AP1*, *AP2*, and *AP3*, since the associated host is near the AP. The maximum power is assigned to *AP4* since the associated host is far from it.

6.5.8 Case 8

Two APs are located in the same room. The same OC is assigned to *AP1* and *AP2*, another OC is assigned to *AP3* and *AP4*. The minimum transmission power is assigned to *AP1* and *AP3* because their associated hosts are in a near position. The maximum power is assigned to *AP2* and *AP4* because their associated hosts are in a different room.

6.5.9 Case 9

Four APs are placed in different rooms. The RSS between them is smaller than the threshold. Thus, the four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1*, *AP2*, and *AP3*, since the associated host is far from the AP. The minimum power is assigned to *AP4* since the associated host is near it.

7 Conclusion

This paper proposed the *joint optimization method of channel assignment and transmission power* for concurrently communicating multiple *access-points (APs)* in the *wireless local-area network (WLAN)*. The extensive experiment results using *Raspberry Pi* APs in various network topologies showed that the proposal always selects the best channel and transmission power for each AP that maximizes the WLAN performance. In future works, we will improve the proposed method by applying simultaneous optimization of channels and transmission powers, using both the bonded and non-bonded channels, MIMO technology, and evaluate the proposal in various network topologies in different network fields.

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