Enhancements of Minimax Access-Point Setup Optimization Approach for IEEE 802.11 WLAN

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Abstract: As a flexible and cost-efficient Internet access network, the IEEE 802.11 *wireless local-area network (WLAN)* has been broadly deployed around the world. Previously, to improve the IEEE 802.11n WLAN performance, we proposed the four-step *minimax access-point (AP) setup optimization approach*: 1) link throughputs between the AP and hosts in the network field are measured manually, 2) the *throughput estimation model* is tuned using the measurement results, 3) the bottleneck host suffering the least throughput is estimated using this model, and 4) the AP setup is optimized to maximize the throughput of the bottleneck host. Unfortunately, this approach has drawbacks: 1) a lot of manual throughput measurements are necessary to tune the model, 2) the shift of the AP location is not considered, and 3) IEEE 802.11ac devices at 5 GHz are not evaluated, although they can offer faster transmissions. In this paper, we present the three enhancements: 1) the number of measurement points is reduced while keeping the model accuracy, 2) the *coordinate* of the AP setup is newly adopted as the optimization parameter, and 3) the AP device with IEEE 802.11ac at 5GHz is considered with slight modifications. The effectiveness is confirmed by extensive experiments in three network fields.

Keywords: Wireless local area network, access-point setup, throughput estimation model, parameter optimization, MIMO.

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1 Introduction

Currently, IEEE 802.11 *wireless local-area network (WLAN)* has been extensively used due to its high data rate, wide coverage area, and backward compatibility Gast (2012). In WLAN, the *receiving signal strength (RSS)* at a host from an *access-point (AP)* may be different depending on the setup of the AP, since the radiation pattern is not symmetric. Hence, the AP setup should be optimized to enhance the RSS at a host and increase the data transmission rate, Lwin et al. (2015) and Funabiki et al. (2016).

Previously, we proposed the *minimax AP setup optimization approach* for IEEE 802.11n WLAN, Lwin et al. (2017). This approach searches for the best setup condition of the AP suffering the minimum throughput, called *bottleneck host*, such that it maximizes the throughput of the host. Then, it is confirmed that the overall host throughput performance of the network is improved.

In this approach, the bottleneck host is extracted using the *throughput estimation model* first, and then, the optimal AP setup is found by manually changing it while measuring the throughput between the AP and the bottleneck host. The model estimates the *receiving signal strength (RSS)* at the host using the *log-distance path loss model* and then, estimates the *throughput* using the *sigmoid function*. Both functions have several parameters to be tuned depending on the target WLAN. To improve the estimation accuracy, Gibney et al. (2010)-Mamun et al. (2016), we proposed the *parameter optimization tool* to find parameter values such that the average error between the measured throughput and the estimated one among the measured host locations becomes minimal.

Unfortunately, the previous study has several drawbacks. First, the throughput measurements for the parameter optimization of *throughput estimation model* are proceeded manually, which requires high labor costs. Thus, the number of measurement locations should be minimized while the estimation accuracy of the model is kept high.

Second, the optimal AP setup condition is found by only changing its *height* and *orientation*, although the *coordinate* can be slightly shifted to improve the *multipath effect*. Besides, only one type commercial AP from NEC with *single-input single-output (SISO)* links is evaluated. Depending on antenna layout designs of APs, the radiation patterns can be different, which suggests the proposed approach should be applied to different vendor APs. Particularly, APs with *multiple-input multiple-output (MIMO)* links providing higher throughputs by multiple data streams, should be verified, Kermoal et al. (2000)-Lo et al. (2012).

Third, only *IEEE 802.11n at 2.4GHz* is considered, although *IEEE 802.11ac at 5GHz* has become popular due to the much higher data rate, using a larger number of antennas for *multiple-input-multiple-output (MIMO)*, the larger *frame aggregation* size, the *beamforming*, and the *multi-user-MIMO (MU-MIMO)*, Gast (2013). For example, the maximum throughput of a commercial AP *NEC WG2600HP* can be $1,733Mbps$ for 11ac at 5GHz and $800Mbps$ for 11n at 2.4GHz, http://www.aterm.jp (2018).

In this paper, we propose the enhancements of the AP setup optimization approach to solve above mentioned drawbacks. First, the procedure of selecting the host locations for the throughput measurement minimization is presented to reduce labor costs. Second, the *coordinate shift* is newly adopted as the optimization parameter in the AP setup optimization, and three different APs from two vendors using MIMO links are newly adopted for evaluations of the proposed approach. Third, we present the application of the minimax AP setup optimization approach to WLAN with IEEE 802.11ac at 5GHz with slight modifications. In our evaluations, three network fields in two buildings in Okayama University are considered.

The rest of this paper is organized as follows: Section 2 presents the related works to this paper. Section 3 reviews the minimax AP setup optimization approach. Section 4 describes the selection procedure of throughput measurement host locations for each AP location in WLAN and evaluations for our proposal in three network fields. Section 5 introduces coordinate optimization as a new AP setup optimization and evaluates with different AP devices for further verifications. Section 6 introduces the application of the minimax approach to 11ac at 5GHz. Finally, Section 7 concludes this paper with future works.

2 Related Works

Several related works to this paper have been reported in literature. Gibney et al. (2010) proposed a network modeling, design, and evaluation tool incorporated with an optimization algorithm based on elements of the artificial intelligence. Their approach optimizes the number of required APs and their positions to meet site-specific demands in indoor environments. Our proposal can be used together to optimize the setup for each allocated AP in the network field.

Sun et al. (2010)-Qin et al. (2010) addressed studies on the radio wave propagation regarding the positions, polarizations, and radiation patterns of transmitting and receiving antennas. They revealed that antenna configurations and orientations cause significant impacts on performances of MIMO links. However, they did not show throughput measurement results for commercial APs using MIMO devices, unlike our paper.

Barbosa et al. (2012) studied the AP placement design in the target network field using two different techniques, namely, a greedy search heuristic (GSA) and a genetic algorithm (GA). Their approach provides the AP design with the maximum coverage area and connected users, and the minimum number of APs and distances from users to their APs. Our proposal can be used together to improve the coverage area of each AP by changing the setup such as the height, the orientation, and the coordinate.

Ma et al. (2013) proposed the optimization of the deployment and transmission power of the AP, to save energy and reduce frequency interferences. They adopted the Fuzzy K-mean algorithm to minimize the number of APs while optimizing the transmission power. On the other hand, our proposal considers the setup optimization of each AP with the maximum transmission power.

Politi et al. (2015) proposed a mathematical model to optimally place an AP with the minimum propagation loss and the signal level at all the receivers in an indoor environment. It minimizes the sum of signal attenuations from the AP when the signal traverses the fewest possible obstacles with large attenuations such as concrete walls and metal cabinets. Our proposal can be used together to further increase the signal level at a receiver by optimizing the setup of the allocated AP in the network field.

Kriara et al. (2016) studied the performance characterization of IEEE 802.11ac WLAN in terms of the throughput, jitter, and fairness using a testbed. They reported that IEEE 802.11ac does not only deliver the higher throughput but also does the fairer one than the earlier standards due to the wider channel bandwidth and higher capacity of the channel bonding. Unfortunately, they did not consider the AP setup optimization.

Simić et al. (2017) examined the combined impact of the channel bandwidth, the traffic profile, and the AP density and placement on the overall throughput and the fairness of the IEEE 802.11ac network. They evaluated the performance of a 24-node large indoor testbed using IEEE 802.11ac. They addressed that wide 80MHz channels are only beneficial for dense deployments of APs with extreme traffic volumes, due to significant adjacent channel interferences. On the other hand, we study the AP setup optimization for IEEE 802.11ac with 80MHz channels at 5 GHz in real office environments.

Newell et al. (2017) carried out performance evaluations of IEEE 802.11n and 11ac networks to characterize the effects of the distance and the interference between different channels. The authors concluded that the throughput performance of the 11ac network at 5GHz decreases extremely fast as the distance from the client to the AP increases, if compared to 11n. On the other hand, we study the AP setup optimization for IEEE 802.11n at 2.4GHz and 11ac at 5GHz.

Commercial WLAN site survey tools, such as NetSpot, https://www.netspotapp.com (2018) and Ekahau HeatMapper, https://www.ekahau.com (2018), have been available. Using these tools, APs are placed in a network field after surveying signal strengths from the allocated APs at the limited positions. Our proposal can be used together to optimize the setup for each allocated AP in the network field.

In our surveys, no paper has discussed the minimax AP setup optimization approach in this paper that optimizes the height, orientation, and coordinates of each allocated AP. Our proposal can be applied to the APs that have been allocated by these existing methods, to further improve the throughput performances.

3 Review of Previous Works

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

3.1 Minimax AP Setup Optimization for 11n at 2.4 GHz

The minimax AP setup optimization approach has been studied for IEEE 802.11n at 2.4GHz that maximizes the overall throughput of the hosts in the network by finding the best setup condition of the AP to the bottleneck host.

3.1.1 Overview

In the approach, first, link throughputs between the AP and some hosts in the network field are measured manually. Next, the *throughput estimation model* is tuned by applying the *parameter optimization tool* with the measured results. Third, the *bottleneck host* suffering the least throughput is detected through simulations using the throughput estimation model. Finally, the setup of the AP is manually optimized to maximize the throughput of the bottleneck host with the AP. It has been confirmed that the AP setup optimization for the bottleneck host can improve the overall throughput to the hosts in the field.

3.1.2 AP Setup Optimization Steps

The minimax AP setup optimization approach consists of the following five steps:

(1) The layout map of the target network field for WLAN is obtained, and the possible locations of the APs and the hosts are identified on the map.

(2) The throughputs between the APs and the hosts in (1) are measured.

(3) The parameters of the throughput estimation model are tuned by applying the parameter optimization tool with the measurement results in (2).

(4) The bottleneck host for each AP is detected using the throughput estimation model. Here, it is assumed that if a host could be associated with multiple APs, the AP that provides the highest throughput in the model is selected.

(5) The setup of each AP in terms of the height and orientation is manually adjusted so that the measured throughput of the corresponding bottleneck host is maximized.

3.2 Throughput Estimation Model

The throughput estimation model estimates the throughput of a wireless communication link between a source node and a destination node in WLAN. First, it estimates the *RSS* at the destination node using the *log-distance path loss model* that considers the distance and the obstacles between the end nodes. Next, it converts the RSS to the throughput using the *sigmoid function*. Both functions possess several parameters that can affect the estimation accuracy.

3.2.1 Signal Strength Estimation

The *RSS* at a host from an AP is calculated using the *log-distance path loss model*, Faria (2005):

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

where P_d represents the RSS (dBm) at the host, α does the path loss exponent factor, d does the distance (m) to the host from the AP, P_1 does the RSS (dBm) at the host at the $1m$ distance from the AP when no obstacle exists between them, n_k does the number of *type k* obstacles along the path between the AP and the host, and W_k does the signal attenuation factor (dB) for the *type k* obstacle. P_1, α, and W_k are parameters to be tuned. To consider the multipath effect, the *indirect path* is also considered by selecting a *diffraction point* for each AP/host pair and select the larger *RSS* between the direct and indirect signals for sigmoid function, Lwin et al. (2017).

It is noted that α can be replaced by α_{inc} (enhanced path loss exponent factor) for $d \geq d_{thr}$ (distance threshold) to improve the estimation accuracy because the prediction accuracy can be poor at longer distances from the transmitter, Sarkar et al. (2003)-Cheung et al. (1998).

3.2.2 Throughput Conversion

The *RSS* is converted to the throughput or data transmission speed between the AP and the host is calculated using the *sigmoid function*:

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

where S represents the estimated throughput (Mbps) when the RSS (dBm) at the host is P_d. a, b, and c are parameters to be tuned.

3.3 Parameter Optimization Tool

The throughput estimation model has several parameters whose values determine the estimation accuracy. In our approach, they are optimized by use of the *parameter optimization tool*, Funabiki et al. (2017), which adopts a local search algorithm that combines the tabu table and the hill climbing procedure to avoid a local minimum. This tool actually can be used for a variety of algorithms/logics that have parameters to be optimized. The program for the tool is independently implemented from the program for the throughput estimation model. It runs the model program as its child process. The optimality of the current parameter values in the model program is evaluated by the throughput estimation error that is given in the output file.

3.3.1 Required Files for Tool

A user of the tool is required to prepare the following five files.

1. Parameter Specification File: This file describes the condition how to change the value of each parameter during the search process. "parameter.csv" must be used as the file name. Each line in this file reflects the specification for one parameter, and must describe in the order of "parameter name", "initial value", "lower limit", "upper limit", and "change step".

2. Model Program File: This file is a binary code file to run the throughput estimation model, which could be executed through the command line. Any name is possible for this file. In addition, this file must satisfy the following two conditions:

   (1) When the program is executed, it receives the path for the parameter file in the argument and applies the parameter values in the file to the model.

   (2) When the program is completed, it outputs the score as the evaluation value in the text file "result.txt".

   With (1), the model program can read the parameter values that are generated by the tool. With (2), the tool can read the score that is calculated in the model program.

3. Sample Input Data File: The sample input data file contains the input data set to the model program such that the result of the program is evaluated and used to optimize the parameter values by the tool. To upgrade the accuracy of the obtained parameter values, multimodal sample input data sets should be collected and adopted in the tool.

4. Score Output File: The score output file involves the score from the model program to evaluate the

current parameter values. The score is given by the difference between measured and estimated throughputs in the throughput estimation model.

5. Script File for Execution: The script file describes the sequence of the commands to execute the model program. The file name must be "run.sh". This file also describes the paths to the input files for the model program. By modifying this script file, the user is able to change the name and the arguments for the model program, and may run multiple programs sequentially to obtain one score. When the model program is executed with multiple sample input data files continuously, the array to describe these files should be prepared and the loop procedure should be adopted.

3.3.2 Processing Flow of Tool

The processing flow of the tool is as follows:

(1) The parameter optimization tool (T) generates the initial parameter file by copying the initial values in the parameter specification file.

(2) T executes the script file using the current parameter file.

- (2-a) The model program (M) reads one sample input data file.
- (2-b) M computes the algorithm/logic.
- (2-c) M writes the score in the score output file.

(3) T reads the score from the score output file.

(4) When the termination condition is satisfied, T goes to (5). Otherwise, T goes to (6).

(5) T changes the parameter file based on the algorithm in the next section, and goes to (2).

(6) T selects the parameter values with the best score and outputs it.

3.4 Drawbacks in Previous Approach

First, throughput measurements in Section 3.1.2 (2) need a lot of manual works. Thus, the number of measured host locations for each AP should be minimized to reduce them.

Second, a small change of the AP location is possible in the real network field, which may drastically improve the *multipath effect*. Thus, the *coordinate shift* should be considered at the AP setup optimization in Section 3.1.2 (5).

Third, the minimax AP setup optimization approach is not applied to IEEE 11ac at 5GHz, although it can provide the much higher throughput than 11n at 2.4GHz. Thus, the minimax approach is applied to 11ac at 5GHz with slight modifications.

4 Throughput Measurement Minimization

In this section, we present the throughput measurement minimization to minimize the number of host locations to tune the throughput estimation model.

4.1 Host Location Selection for Measurement Minimization

The throughput estimation model has several parameters whose values must be tuned from measured throughputs: the path loss exponent factor α, the RSS at the host at the $1m$ distance from the AP P_1, and the signal attenuation factor W_k for walls with various types and the diffraction point. Thus, the following host locations should be selected for throughput measurements to tune these parameters:

(1) For each room in the field, the host location nearest from the AP should be selected to determine the path loss exponent factor, the $1m$ distance RSS, and the three sigmoid function parameters.

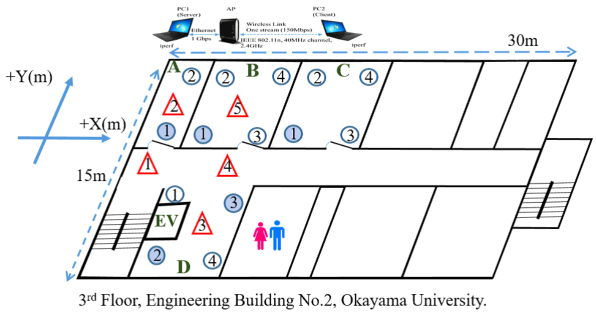
(2) For each wall type, the host location across the type wall from the AP should be selected to determine the attenuation factor.

(3) For each diffraction point, the host location nearest from the AP in the room should be selected to determine the attenuation factor at the diffraction point to reflect multipath effect, where the direct path from the AP passed through three or more walls.

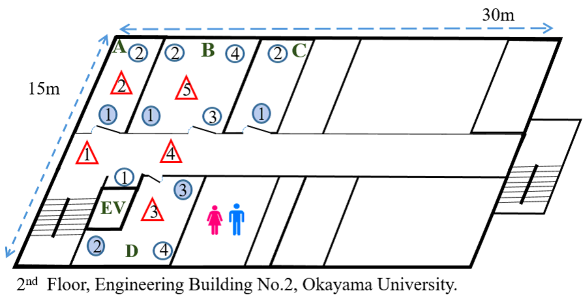
4.2 Network Fields and Devices for Evaluations

The effectiveness of this proposal is evaluated in three network fields. Figure 1 shows them, namely field#1, field#2 and field#3. The triangle represents the AP and the circle does the host location. Five AP locations are considered in each field. 14 host locations are considered for throughput measurements in field#1, 12 locations are in field#2, and 16 locations are in field#3. The *diffraction point* for each host is manually selected.

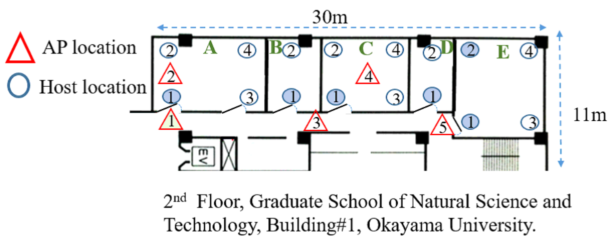
For the AP, NEC WG2600HP with four internal antennas is used, http://www.aterm.jp (2018). For the host, a laptop PC with Windows OS is used, where Qualcomm Atheros AR9285 IEEE802.11b/g/n wireless adapter is used for SISO, Dual Band Wireless-AC 8260 wireless adapter is for 2×2 MIMO, and the 40MHz bonded channel at 2.4 GHz is used for any link. The software tool *iPerf*, https://iperf.fr (2018), is used for throughput measurements by generating TCP traffics for $50sec$ with $477Kbytes$ window size and $8Kbyte$ buffer size. During measurements, *iPerf* is run for only one link between the server and each client host, to consider the single link communication for the throughput estimation model. It is noted that all the experiments were conducted on weekends to reduce the interferences from other wireless devices and human movements.



(a) network field#1



(b) network field#2



(c) network field#3

Figure 1: Three network fields.

4.3 Host Location Selection Result

The host locations for the throughput measurement minimization are selected by following the procedure in Section 4.1 in the three fields. Five locations are selected in field#1 and field#2, and six locations are in field#3. For example, the shaded circle in Figure 1 indicates the selected host location for AP1 respectively.

4.4 Parameter Optimization Result

First, the values of the parameters in the model, P_1, α, W_k, W_{dif}, a, b, and c, are optimized by applying the parameter optimization tool using the measured data in the field. As the wall type, the corridor wall (W_1), the partition wall (W_2), the intervening wall (W_3), the glass wall (W_4), the elevator wall (W_5) and the door (W_6) are examined. W_{dif} is the common attenuation factor for the diffraction points. In this paper, to improve the accuracy of the estimation model, the door of the room is added as another wall type that has a significant effect on the RSS, Alhamoud et al. (2014).

Tables 1 and 2 compare the parameter values that were obtained by applying the parameter optimization tool to the measurement results at all the host locations (*all*) and to those at the selected locations by the proposal (*proposal*) for each AP using SISO links and MIMO links respectively. They reveal that the values of the path loss exponent and the attenuation factors are similar between *all* and *proposal*. The validity of the host location procedure in Section 4.1 is confirmed.

Table 1 Parameter optimization result for SISO link.

	field#1		field#2		field#3	
para-	# measured hosts		# measured hosts		# measured hosts	
meter	all	proposal	all	proposal	all	proposal
P_1	-35.9	-35.8	-37.6	-37.7	-34	-35.1
α	2.00	2.00	2.00	2.00	2.00	2.00
α_{inc}	2.10	2.10	2.10	2.10	2.04	2.01
d_{thr}	5	5.2	6.5	5.2	5	5
W_1	7	7	7	7	8	6
W_2	7	8	7	7	5	4
W_3	8	8	10	9	-	-
W_4	-	-	2	2	-	-
W_5	2.9	2	2.8	2.0	-	-
W_6	2	3	5.0	3.7	2	2.8
W_{dif}	2	2	2	2	3.1	2
a	90	90	85	85	98	94
b	55	53.5	50	52	40	44.5
c	8	8	8	8	7.5	8

Table 2 Parameter optimization result for MIMO link.

	field#1		field#2		field#3	
para-	# measured hosts		# measured hosts		# measured hosts	
meter	all	proposal	all	proposal	all	proposal
P_1	-34.0	-35.6	-36.2	-35.2	-35.2	-34
α	2.39	2.09	2.31	2.20	2.00	2.10
α_{inc}	2.49	2.19	2.41	2.40	2.10	2.20
d_{thr}	5	5	7	5.2	6.3	5
W_1	7	7	7	7	7	7
W_2	8	8	8	8	5	5
W_3	7	7	7	7	-	-
W_4	-	-	3.0	2	-	-
W_5	2	2	3.2	2.8	-	-
W_6	4.7	3	3.7	3	2	2
W_{dif}	1.9	2	1.5	2	2	1.9
a	190	190	190	190	195	194
b	47	46.5	47.5	50	40	40
c	6.5	7	6	8	6.5	6.5

4.5 Throughput Estimation Results

Subsequently, the throughput is estimated by using the throughput estimation model with the parameter values in Table 1 for SISO links and Table 2 for

MIMO links. To verify the accuracy of the model, the throughput estimation error (Mbps) given by the difference between the measured throughput and the estimated one is calculated.

Tables 3 and 4 summarize the average, the maximum, the minimum, the standard deviation (SD), and the coefficient of variation (CV) of the errors for all the links between the host locations and each AP. In any field, the estimation accuracy of the model is similar between *all* and *proposal* for both SISO and MIMO links. It indicates that the accuracy of the model is not lowered by the proposal. Thus, the effectiveness of our proposal in reducing labor costs is confirmed.

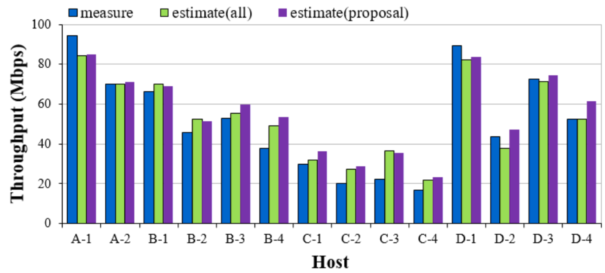
In field#3, the estimation accuracy is better than other two fields, because fewer obstacles such as tables, bookshelves, and equipment exist there. The estimation accuracy of SISO links is higher than that of MIMO links, because of the use of the *sigmoid function* in the throughput estimation model. The throughput of the 2×2 MIMO link becomes double of that of the SISO link, whereas the RSS range is the same, Debnat et al. (2018). As a result, the estimated throughput can be widely changed even if the RSS is slightly changed. Thus, a small error of the estimated RSS can magnify the error of the estimated throughput for MIMO links.

Table 3 Throughput estimation errors (Mbps) for SISO links.

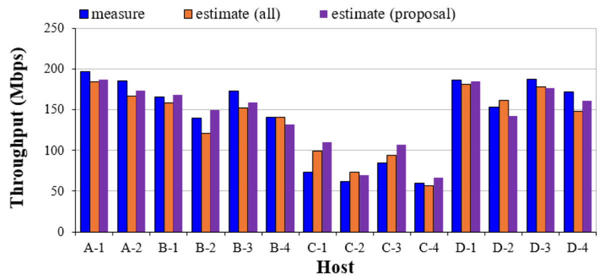
field	AP	para. set	measure	estimation errors				
			avg. TP	avg.	max	min	SD	CV (%)
field#1	AP1	all	50.98	5.72	14.11	0.01	4.44	8.71
		proposal	50.98	7.04	15.80	1.21	4.28	8.39
	AP4	all	59.65	9.55	24.86	0.53	7.73	12.96
		proposal	59.65	8.83	26.76	0.46	8.12	13.61
	AP5	all	78.08	11.65	24.67	0.03	7.74	9.91
		proposal	78.08	11.43	29.45	0.79	8.07	10.34
field#2	AP1	all	40.83	12.19	22.92	1.05	7.89	19.32
		proposal	40.83	11.52	20.85	0.21	6.35	15.55
	AP4	all	50.29	9.53	18.38	3.49	5.79	11.51
		proposal	50.29	8.66	25.37	0.31	8.36	16.62
	AP5	all	82.58	12.85	21.91	4.87	5.38	6.51
		proposal	82.58	14.81	21.52	4.86	5.14	6.22
field#3	AP1	all	64.26	7.29	12.91	1.88	3.36	5.23
		proposal	64.26	7.32	13.08	0.09	3.50	5.45
	AP4	all	78.64	4.93	12.25	0.22	3.36	4.27
		proposal	78.64	4.57	11.44	0.01	3.42	4.35
	AP5	all	69.46	7.45	19.84	0.24	6.79	9.78
		proposal	69.46	7.59	19.09	1.38	6.54	9.42

Table 4 Throughput estimation errors (Mbps) for MIMO links.

field	AP	para. set	measure	estimation errors				
			avg. TP	avg.	max	min	SD	CV (%)
field#1	AP1	all	139.63	12.48	25.66	0.24	7.83	5.61
		proposal	139.63	11.83	36.58	2.11	8.65	6.19
	AP4	all	155.36	9.09	18.18	0.30	5.67	3.65
		proposal	155.36	8.61	24.82	0.39	6.94	4.47
	AP5	all	158.92	8.36	31.07	0.29	9.06	5.70
		proposal	158.92	11.25	34.40	1.74	10.89	6.85
field#2	AP1	all	141.28	12.01	20.82	3.26	6.46	4.57
		proposal	141.28	15.78	24.64	3.92	6.34	4.49
	AP4	all	166.00	10.27	19.96	1.85	6.59	4.04
		proposal	166.00	12.29	20.46	2.58	6.65	3.76
	AP5	all	161.65	10.91	30.42	0.58	9.49	5.87
		proposal	161.65	10.08	22.18	0.58	7.93	4.91
field#3	AP1	all	147.17	10.16	16.12	0.42	4.40	2.99
		proposal	147.17	12.18	20.32	0.01	5.59	3.80
	AP4	all	171.43	9.63	29.29	0.36	8.96	5.23
		proposal	171.43	9.06	28.14	0.43	7.97	4.65
	AP5	all	161.56	9.74	21.55	0.53	6.94	4.30
		proposal	161.56	9.69	24.80	0.24	7.54	4.69



(a) SISO links



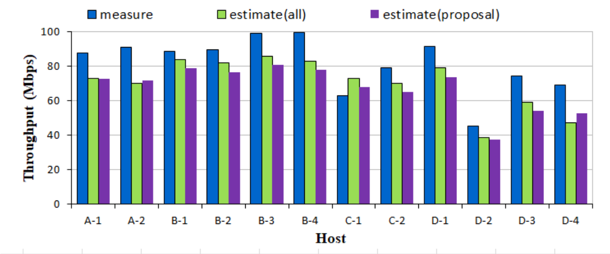
(b) MIMO links

Figure 2: Measured and estimated throughput for AP1 in field#1.

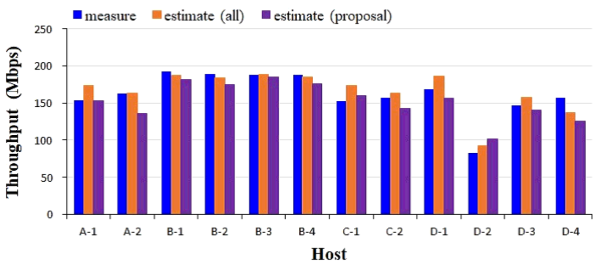
For reference, Figures 2-4 show the measured throughput, the estimated one by all the host locations, and the estimated one by the proposal at every host location for AP1 in field#1, AP5 in field#2, and AP1 in field#3 respectively. These throughputs are similar to each other, which confirms the effectiveness of the proposal.

4.6 Bottleneck Host Results

Finally, in Table 5, the bottleneck host detection for each AP was verified. As shown in Figures 2-4, for any AP location, the bottleneck host providing the lowest throughput by the proposal is coincident with the one by the measurements.

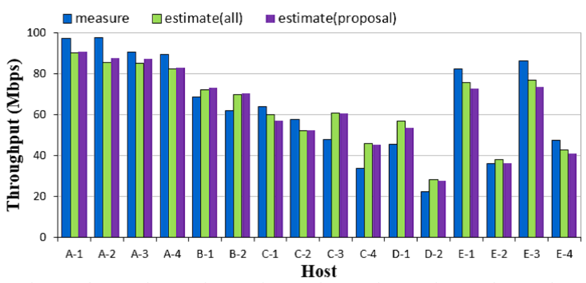


(a) SISO links

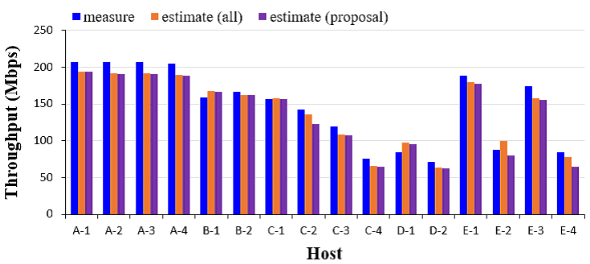


(b) MIMO links

Figure 3: Measured and estimated throughput for AP5 in field#2.



(a) SISO links



(b) MIMO links

Figure 4: Measured and estimated throughput for AP1 in field#3.

5 Coordinate Shift Optimization

In this section, we present the *coordinate shift* as a new optimization parameter in the AP setup optimization approach. In this paper, we only consider the AP locations in the corridor where the sufficient space is available for the coordinate shift optimization.

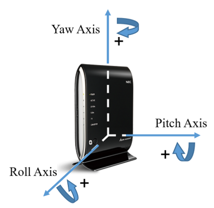
Table 5 Bottleneck host for APs in fields

field	AP	bottleneck host
field#1	AP1	C4
	AP4	A2
	AP5	D2
field#2	AP1	C2
	AP4	A2
	AP5	D2
field#3	AP1	D2
	AP4	A1
	AP5	A2

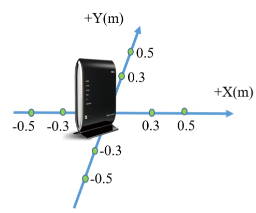
For the AP locations inside the room, it is difficult to apply the coordinate shift optimization due to tables, desks, and sofas that are fixed there. It will be in future works.

5.1 *Effect of Coordinate Shift*

The *multipath effect* can take an important role in improving the throughput performance of a wireless link. It can be changed by the surrounding environment of the AP in the field. Thus, even if the AP is shifted slightly, it may drastically change the multipath effect and affect the performance. To consider the limitation of the possible AP location due to the power supply and the available space, it is assumed that any AP can be sifted by $\pm 0.3m$ or $\pm 0.5m$ along the x or y axis from the original location as shown in Figure 5 (b).



(a) Orientation change



(b) Coordinate shift

Figure 5: AP setup optimization parameters.

5.2 *Results at Bottleneck Host*

The coordinate of the AP is manually shifted by $\pm 0.3m$ or $\pm 0.5m$ along the x or y axis from the original one, and the throughput of the link between the bottleneck host and the AP at each location is measured. Tables 6 and 7 show the throughput results of the bottleneck host, when the devices and software in Section 4.2 are used and the coordinate is shifted along x axis and y axis.

They indicate that the throughput can be improved by shifting the coordinate properly, especially along the x-axis. This reason is that all of the AP locations exist in the corridor where the signal can more strongly propagate along the corridor. Besides, the rooms exist on both side of the corridor along the x-axis. On the other hand, when the AP is shifted along the y-axis, it becomes closer to the center of the corridor, which is farer from the rooms.

Table 6 Throughputs (Mbps) by coordinate shift along x-axis.

field	AP	shifting size (m) -0.5	-0.3	0	0.3	0.5
field#1	AP1	33.50	35.30	37.08	32.40	30.90
	AP4	48.00	39.90	33.32	42.80	35.00
field#2	AP1	27.10	27.00	22.68	12.40	34.00
	AP4	36.60	28.40	37.66	53.50	26.50
field#3	AP1	44.60	45.80	43.97	37.60	49.70
	AP5	43.20	46.00	61.50	47.40	37.50

Table 7 Throughputs by coordinate shift along y-axis.

field	AP	shifting size (m) -0.5	-0.3	0	0.3	0.5
field#1	AP1	36.10	20.40	37.08	28.30	30.90
	AP4	42.60	30.52	33.32	36.40	32.40
field#2	AP1	46.70	26.00	22.68	36.90	34.20
	AP4	39.00	43.20	37.66	37.50	26.40
field#3	AP1	47.60	49.60	43.97	45.10	41.40
	AP5	48.10	56.20	61.50	33.50	43.70

5.3 Results at All Hosts

Including the coordinate shift, the setup condition of each AP is optimized manually to maximize the throughput of the bottleneck host. To evaluate the effectiveness in the whole network, the average throughput improvement among all the hosts is investigated for each AP. Tables 8 and 9 show the average throughputs of three cases, 1) the original setup, 2) after the height and orientation optimizations (after H&O), and 3) after all the optimizations (after ALL), where the improvement rates from 1) to 2), and those from 2) to 3) are compared.

The results indicate that the coordinate shift optimization can further improve the average throughput in any AP. Specifically, for AP4 in field#2 for SISO links, the average throughput is improved from 52.17$Mbps$ to 69.60$Mbps$. However, in some APs, the coordinate shift does not improve it. In general, the coordinate shift does not much improve the throughput for MIMO links, because using the multiple antennas, the multipath effect is not sensitive to the link environment.

5.4 Results at All Hosts Using Different APs

The effectiveness of the proposal is examined using three commercial APs from two vendors

Table 8 Average throughput improvement of SISO links for NEC-AP.

field	AP	1) original setup (Mbps)	2) after H&O (Mbps)	imp. rate from 1) (%)	3) after ALL (Mbps)	imp. rate from 2) (%)
field#1	AP1	51.06	65.23	27.77	65.23	0.00
	AP4	57.90	67.29	16.22	71.18	5.78
field#2	AP1	40.48	52.88	30.66	61.87	16.99
	AP4	49.09	52.17	6.28	69.60	33.42
field#3	AP1	64.26	70.42	9.59	73.39	4.23
	AP5	69.55	78.63	13.06	78.63	0.00

Table 9 Average throughput improvement of MIMO links for NEC-AP.

field	AP	1) original setup (Mbps)	2) after H&O (Mbps)	imp. rate from 1) (%)	3) after ALL (Mbps)	imp. rate from 2) (%)
field#1	AP1	139.63	145.94	4.51	145.94	0.00
	AP4	155.36	179.86	15.77	182.00	1.19
field#2	AP1	141.28	155.59	10.13	160.33	3.05
	AP4	166.00	174.92	5.37	174.92	0.00
field#3	AP1	147.17	156.38	6.26	156.38	0.00
	AP5	161.56	169.43	4.87	171.00	0.93

in the same fields using MIMO links: *Buffalo WZR-1750DHP*, http:manual.buffalo.jp (2018), *IO-Data WNAC1600DGR3*, http://www.iodata.jp (2018), and *IO-Data WN-AX2033GR*, http://www.iodata.jp (2018). Due to the hardware trouble, the last AP was used only in field#3.

Tables 10 and 11 show the average throughput improvements for them. The results indicate that the coordinate optimization can improve for any AP except *Buffalo-AP1* in field#2 and *IO-Data-AP4* in field#1. For *Buffalo-AP4* in field#1, the average throughput is improved from 168.34$Mbps$ to 171.64$Mbps$, which means 1.96% improvement. For *IO-Data-AP1* in field#1, it is improved from 146.91$Mbps$ to 154.15$Mbps$, which means the 4.93% improvement. The setup optimization approach is effective in various APs.

Table 10 Average throughput improvement for *Buffalo-AP*.

field	AP	1) original setup (Mbps)	2) after H&O (Mbps)	imp. rate from 1) (%)	3) after ALL (Mbps)	imp. rate from 2) (%)
field#1	AP1	144.79	155.85	7.64	158.20	1.51
	AP4	157.94	168.34	6.58	171.64	1.96
field#2	AP1	153.15	171.00	11.66	171.00	0.00
	AP4	165.17	169.48	2.61	170.92	0.85
field#3	AP1	152.04	158.22	4.07	160.80	1.63
	AP5	152.94	155.83	1.89	156.50	0.43

Table 11 Average throughput improvement for *IO-Data-AP*.

field	AP	1) original setup (Mbps)	2) after H&O (Mbps)	imp. rate from 1) (%)	3) after ALL (Mbps)	imp. rate from 2) (%)
field#1	AP1	136.61	146.91	7.54	154.15	4.93
	AP4	149.31	163.43	9.46	163.43	0.00
field#2	AP1	139.16	144.39	3.76	147.02	1.82
	AP4	149.53	161.75	8.18	164.00	1.39
field#3	AP1	134.25	141.01	5.03	143.89	2.04
	AP5	131.06	133.76	2.06	134.65	0.67

6 Minimax AP Setup Optimization for 11ac at 5GHz

In this section, we present the application of the minimax AP setup optimization approach to IEEE 802.11ac at 5GHz.

6.1 Throughput Measurement Results for 11ac at 5GHz

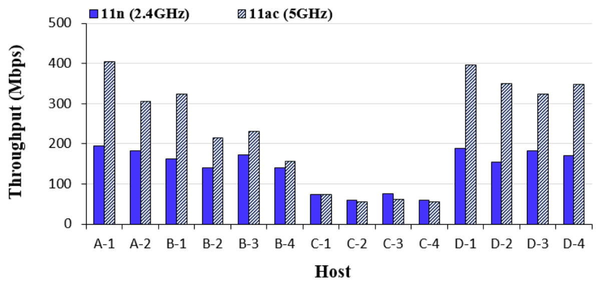
To investigate the performance of IEEE 802.11ac at 5GHz with the 80MHz channel as the default setting, where four 20MHz channels are bonded, we conduct the measurements in indoor network fields using the devices and software tools in Section 4.2. It is noted that they support 11ac. We compare with the measured throughput results for 11n at 2.4GHz.

Figure 6 shows measured throughput results for AP1 in field#1 and field#3 in Figure 1. They demonstrate that when the host is near the AP such as A-1 in both fields, the throughput of 11ac becomes more than double of that of 11n due to the wider channel bandwidth. However, as the distance between the host and the AP becomes larger, the throughput advantage of 11ac becomes smaller due to the larger attenuation with the higher frequency. Furthermore, at certain host locations such as C-2, C-3 in field#1 and D-2, E-2, E-4 in field#3 where several walls exist along the line-of-sight from the AP, the throughput for 11ac becomes smaller than that for 11n.

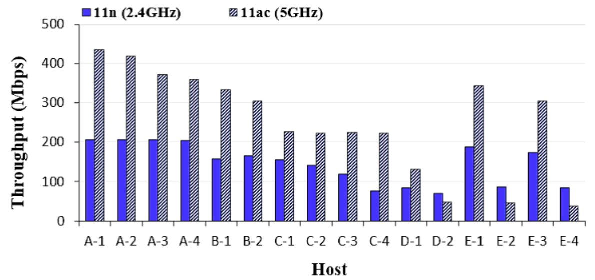
6.1.1 Slow Host Exclusion for 11ac at 5GHz

As observed in Figure 6, the throughput for 11ac at 5GHz is smaller than that for 11n at 2.4GHz at some host locations. It is better to use 11n at 2.4GHz for the better performance. Besides, the throughput estimation model may not be accurate for such slow links, because the RSS at the host becomes too small due to the larger path loss at the higher frequency.

Therefore, in this paper, any host location whose throughput is smaller than $100 Mbps$, is excluded from the scopes of the throughput estimation model and the bottleneck host selection. Actually, C-1, C-2, C-3, C-4 for AP1 in field#1 and D-2, E-2, E-4 for AP1 in field#3



(a) AP1 in field#1



(b) AP1 in field#3

Figure 6: Throughput measurement results for 11n and 11ac.

are excluded. It is noted that $100 Mbps$ is selected from the results in Figure 6.

6.2 Throughput Estimation Model for 11ac at 5GHz

Next, we discuss the throughput estimation model for 11ac at 5GHz.

6.2.1 Model Parameter Optimization Results

The parameters of the throughput estimation model for 11ac at 5GHz are optimized using the *parameter optimization tool* with the measurement results that follow Section 4.1. Table 12 shows the values. It is observed that α_{inc} (larger path loss exponent factor) is larger than that for 11n at 2.4GHz, because of the larger path loss. The value of a in the sigmoid function is more than double due to the larger throughput range.

6.2.2 Throughput Estimation Results for 11ac at 5GHz

Then, the estimated throughput results by the model are compared with the measurement results. Table 13 summarizes the average, the maximum, the minimum, the standard deviation (SD), and the coefficient of variation (CV) of the throughput estimation errors (Mbps) for each AP. The CV is similar between 11ac at 5GHz and 11n at 2.4GHz for most APs. Figure 7 shows the measured and estimated throughput results for AP1 in field#1 and field#3. It indicates that the estimation error for the slow host whose throughput is smaller than $100 Mbps$ is large.

Table 12 Parameter optimization results for 11ac at 5GHz.

parameter	field#1	field#2	field#3
P_1	-35.1	-34	-34
α	2.00	2.00	2.00
α_{inc}	2.50	2.50	2.50
d_{thr}	5	4	5
W_1	8	8	7
W_2	8	8	6
W_3	7	6	-
W_4	-	2	-
W_5	2	2	-
W_6	2.6	2.5	3
W_dif	2	1	1
a	445	437	452
b	53.5	51.5	42.0
c	9	8	9

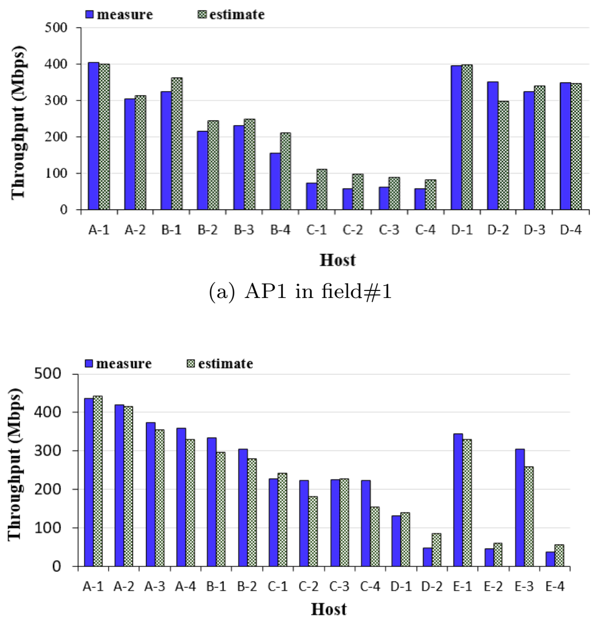
Besides, for any AP, the bottleneck host found by the model is coincident with the one by the measurement. Specifically, in field#1, B-4 is the bottleneck host for AP1, and A-2 is for AP4. In field#2, C-2 is for AP1, and A-2 is for AP4. In field#3, D-1 is for AP1, and A-2 is for AP5. These results justify the use of the throughput estimation model in the minimax AP setup optimization approach for 11ac at 5GHz.

Table 13 Throughput estimation errors (Mbps) for 11ac at 5GHz.

field	AP	measure	estimation errors				
		avg. TP	avg.	max	min	SD	CV (%)
field#1	AP1	305.20	22.49	53.91	1.88	20.04	6.57
	AP4	305.43	25.26	66.49	0.02	17.81	5.83
field#2	AP1	298.42	24.91	66.68	2.82	16.31	5.47
	AP4	319.92	19.63	41.90	4.12	12.16	3.80
field#3	AP1	302.85	23.57	69.73	2.15	20.51	6.77
	AP5	349.25	33.64	62.33	5.00	15.69	4.49

6.3 AP Setup Optimization Results for 11ac at 5GHz

Finally, the minimax AP setup optimization approach is applied to 11ac at 5GHz in the three network fields. Table 14 shows the average throughput improvements, which indicates that our approach can improve the average throughput in any AP. For AP4 in field#2, the average throughput is improved from 319.92$Mbps$ to 350$Mbps$, which means 9.4% improvement. Figure 8 compares the measured throughput for AP1 in field#1 and field#3 before and after applying the approach. It can be noticed that throughputs after the application become more averaged among the host locations than those before optimization. Thus, the effectiveness of the minimax AP setup optimization approach is confirmed for IEEE 802.11ac at 5GHz.



(a) AP1 in field#1

(b) AP1 in field#3

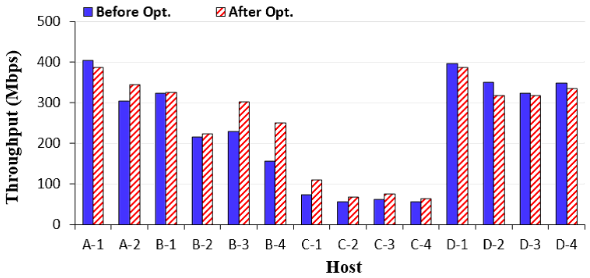
Figure 7: Measured and estimated throughput for 11ac at 5GHz.

Table 14 Average throughput improvement of 11ac at 5GHz.

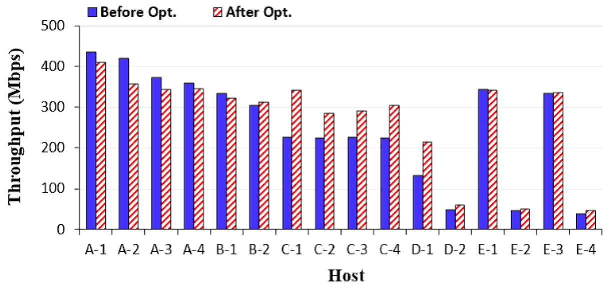
field	AP	1) original setup (Mbps)	2) after H&O (Mbps)	imp. rate from 1) (%)	3) after ALL (Mbps)	imp. rate from 2) (%)
field#1	AP1	305.20	315.40	3.34	318.60	1.01
	AP4	305.43	317.29	3.88	317.29	0.00
field#2	AP1	298.42	310.33	3.99	317.75	2.39
	AP4	319.92	350.00	9.40	350.00	0.00
field#3	AP1	302.85	317.38	4.80	323.31	1.87
	AP5	349.25	354.13	1.40	354.13	0.00

7 Conclusion

This paper presented the three enhancements of the minimax AP setup optimization approach for IEEE 802.11n/ac WLAN. First, the throughput measurements minimization procedure is presented to minimize the workload for parameter optimizations of the throughput estimation model. Second, the coordinate shift is newly considered as an optimization parameter in the AP setup optimization. Third, the minimax AP setup optimization approach is applied to IEEE 802.11ac at 5GHz with slight modifications. Extensive experiment results in three network fields confirmed the effectiveness of them. In future works, the approach will be extended to the multiple APs setup optimization.



(a) AP1 in field#1



(b) AP1 in field#3

Figure 8: Throughput improvement for 11ac at 5GHz.

Acknowledgments

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