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# A Holding Access-Point Assignment Algorithm for IEEE802.11 Wireless Local-Area Networks

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**Abstract:** Nowadays, various types of *access-points (APs)* and hosts such as dedicated APs, laptop personal computers (PCs), and mobile terminals have been used in *IEEE802.11 wireless local-area networks (WLANs)*. As a result, the optimal assignment of holding APs with different types into the network field, depending on the host type distribution, has become another important task to design high-performance WLANs. In this paper, we first define this *holding access-point assignment problem* as a combinatorial optimization problem and propose its two-phase heuristic algorithm. Then, since plural partially overlapping channels are available in IEEE802.11 WLANs, we present the channel assignment extension to the APs such that the communication time of the APs is minimized, and the model to estimate the communication time increase by interferences. The effectiveness of our proposal is verified through simulations in six instances using the WIMNET simulator.

**Keywords:** Wireless Local-Area Network; Holding Access-Point; Partially Overlapping Channel; Assignment Algorithm; Combinatorial Optimization Problem.

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## 1 Introduction

Recently, new *access-point (AP)* devices providing higher performances and advanced functions have become available within short time for *wireless local-area networks (WLANs)*, due to the rapid developments of the technologies for device manufacturing, wireless communications, and supporting software. As a result, many organizations including governments, companies, and schools have a variety of AP devices that have different communication performances and specifications, due to the implemented communication protocols and the adopted number of adopted MIMO (Multiple-Input-Multiple-Output) antennas. Currently, IEEE802.11g, 11n, and 11ac protocols have been practically used in WLANs. Among them, 11n and 11ac allows the use of MIMO antennas to increase the communication capacity by realizing plural streams between the source and destination nodes using multiple antennas E. Perahia et al. (2008); M. Gast (2013); R. V. Nee (2011); O. Bejarano et al. (2013); Q. H. Spencer et al. (2004); T. Hiraguri et al. (2015).

At the same time, the variation of client hosts for WLANs has been also increased. Traditionally, laptop personal computers (PCs) have been used as client hosts. In addition, smart phones and tablet terminals have often been used there. These hosts also support different protocols and have the different number of antennas.

Basically, the highest communication speed of a wireless link between an AP and a host can be confined by the lower specification of either device of the link. For example, when the AP supports IEEE802.11ac with three antennas and the host does IEEE802.11n with two antennas, they can communicate with the lower specification of 11n with two antennas. In this case, the lower-spec AP supporting 11n with two antennas can be assigned there to provide the same communication speed, while the higher-spec AP supporting 11ac with three antennas should be assigned at other places where hosts supporting 11ac are available. As a result, the proper assignment of the holding APs in the network field is another important task in designing high-performance WLANs, so that the wireless links between APs and hosts can perform with the highest specifications as best as possible.

In IEEE802.11 WLANs, a limited number of frequency channels is available. Actually, in Japan, only 13 channels can be used for 2.4GHz bands, and 19 channels can be for 5GHz bands, when 20MHz band is allocated for one channel. The frequency bands of the adjacent channels are partially overlapping as shown in Figure 1 Cisco Systems, Inc. (2016), and thus, the links using close channels can cause interferences when they communicate at the same time. Thus, the proper channel assignment to the APs is also critical for high-performance WLANs.

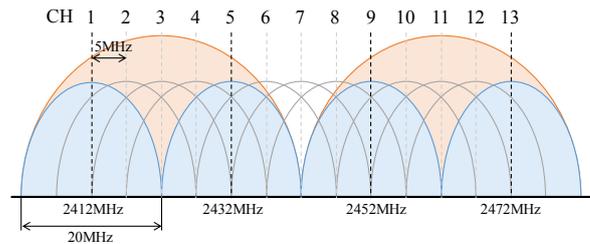


Figure 1 Partially overlapping channels for 2.4GHz.

In this paper, first, we define the *holding AP assignment problem* as a new combinatorial optimization problem for designing high-performance WLANs, where the inputs, outputs, constraints, and objectives of the problem are formulated. In this formulation, it is assumed that the network layout information including the locations of the APs and the hosts is given as the inputs, and the link speed for any pair of an AP and a host can be calculated using the formula in N. Funabiki et al. (2012) from it. Besides, it is assumed that only one channel can be used for all the devices in the network for simplicity. Then, we propose the heuristic algorithm for this problem that consists of the greedy initialization phase and the local search optimization phase.

Next, to consider the optimal channel assignment to the APs, we present the *channel assignment extension* of the algorithm such that the communication time of the APs is minimized, and the model to estimate the communication time increase by the interference in partially overlapping channels. The effectiveness of our proposal is verified through simulations in simple instances using the WIMNET simulator.

The rest of this paper is organized as follows: Section 2 presents the holding AP assignment algorithm for WLANs Sections 3 and 4 present the channel assignment extension and the model for partially overlapping channels respectively. Section 5 shows the simulation results for evaluations. Section 6 provides concluding remarks with future works.

## 2 Holding AP Assignment Algorithm

In this section, we define the holding AP assignment problem and present its heuristic algorithm for high-performance WLANs.

### 2.1 Device Type

The maximum throughput of a wireless communication link can be drastically changed, depending on the protocol, the frequency, and the number of antennas adopted in the devices of the end nodes of the link. In this paper, each combination of these factors is represented by a *device type* (or type) with a unique index number. Table 1 shows the eight types that are considered in this paper. The type with the larger index represents newer

**Table 1** Device type.

type	protocol	frequency	# of antennas	max. speed (Mbps)
1	11a	5.0	1	54
2	11g	2.4	1	54
3	11n	2.4	1	150
4	11n	2.4	2	300
5	11n	2.4	3	450
6	11ac	5.0	1	433
7	11ac	5.0	2	867
8	11ac	5.0	3	1300

technologies that can provide higher performances than the type with the smaller index. Because of the lower type compatibility in WLAN devices, the maximum throughput of a link is determined by that of the device with the smaller index between the two end devices.

This paper assumes that the standard device type exists, such that the link speed change with the distance and the path obstacles between the end nodes is analyzed using the measurement results of the devices with this type, and is well modeled. Using the link speed model for the standard type, the link speed for any type can be calculated. In this paper, the type 3 is actually selected as the standard one.

## 2.2 Problem Formulation

In order to improve the performance of a WLAN, APs with larger indices should be assigned to the places in the network field where many hosts with larger indices exist, if the number of such APs is small among the holding ones. As a result, the optimal assignment of holding AP types becomes an important task to be solved. The optimal holding AP assignment problem can be defined as a combinatorial optimization problem as follows:

- Input:
  - $Ha_k$ : the number of holding APs with type  $k$ ,
  - $Hh_k$ : the number of hosts with type  $k$  in the field,
  - $La_i$ : the  $i$ -th AP location,
  - $Lh_j$ : the  $j$ -th host in the field,
  - $ht_j$ : the type of the  $j$ -th host,
  - $m_k$ : the maximum link speed of type  $k$ ,
  - $K$ : the type for the standard link speed,
- Output:
  - $at_i$ : the assigned type to the  $i$ -th AP location  $La_i$ ,
  - $Ah_j$ : the connecting AP placement of the  $j$ -th host  $Lh_j$ .
- Constraint:
  1. The number of assigned APs with type  $k$  must be equal to or less than  $Ha_k$ ,

2. Every host must be connected to one AP placement.

- Objective: to minimize the cost function  $E$  in Eq. (1).

$$E = A \sum_i \sum_{j \in AP_i} \frac{1}{sa_{ij}} + B \max_i \left[ \sum_{j \in AP_i} \frac{1}{sa_{ij}} \right] \quad (1)$$

where  $A$  and  $B$  represent the constant coefficients ( $A = 5$  and  $B = 1$  in this paper),  $AP_i$  does the set of hosts connected to  $La_i$ ,  $\max_i[\ ]$  returns the maximum value on  $i$ ,  $sa_{ij}$  does the link speed between AP  $La_i$  and host  $Lh_j$  that can be calculated by Eq. (2):

$$sa_{ij} = sd_{ij} \frac{\min(m_{at_i}, m_{ht_j})}{m_K} \quad (2)$$

where  $sd_{ij}$  represents the standard link speed between  $La_i$  and  $Lh_j$ ,  $m_{at_i}$  and  $m_{ht_j}$  do the maximum link speed of the AP assigned to  $La_i$  and the host to  $Lh_j$ , and  $m_K$  does the maximum link speed of the standard type. The  $A$ -term in  $E$  represents the total delay time and the  $B$ -term does the maximum delay time of one AP when all the hosts are communicating at the same time.

## 2.3 Algorithm

The two-stage heuristic algorithm that is composed of the greedy method and the simulated annealing (SA), is presented for the holding AP assignment problem.

### 2.3.1 Initial Solution by Greedy Method

In our algorithm, first, the initial solution is constructed by assigning the currently available AP with the highest performance or type index to the most congested unassigned AP location in the field.

1. Calculate the standard link speed ( $sd_{ij}$ ) for every pair of the AP location and the host, assuming the standard-type AP and host, by using the formula in N. Funabiki et al. (2012) from the layout information of the network.
2. Sort the holding APs in descending order of the maximum link speed.
3. Calculate the actual link speed ( $sh_{ij}$ ) for every pair of the AP location and the host considering their types by:

$$sh_{ij} = sd_{ij} \frac{m_{ht_j}}{m_K} \quad (3)$$

4. Select the AP location that provides the largest maximum link speed in 3 for each host and associate the host to the corresponding AP location.

5. Count the number of hosts associated with each AP location in 4 and sort the AP locations in descending order of this number.
6. Assign a holding AP to each AP location sequentially:
  - (a) Select the first unassigned AP location in the sorted list.
  - (b) Assign an unassigned AP whose type is equal to or larger than the type of any host associated with the selected AP location.
  - (c) If no such AP exists, assign an unassigned AP whose type has the minimum difference from the type of any host associated with the selected AP location.
7. Calculate the real link speed  $sa_{ij}$  for each pair of an assigned AP and a host by Eq. (2).
8. Calculate the cost function  $E$  in Eq. (1).
9. Save the solution as the best solution  $S_{best}$  and the cost  $E$  as the best cost  $E_{best}$ .

### 2.3.2 Solution Improvement by SA

Next, the initial solution is iteratively improved by SA, where the following parameters are used:

- $L_{max}$ : the local minimum convergence parameter ( $L_{max} = 10000$  in the paper),
  - $RN$ : the number of iterations ( $RN = 8000000$ ),
  - $Tp$ : the SA temperature ( $Tp = 0.00013$ ).
1. Initialize the iteration counter  $I_{cnt}$  and the local minimum counter  $L_{cnt}$  by 0.
  2. Generate a neighbor solution from the current one.
    - (a) If  $L_{cnt} < L_{max}$ , change the associated AP of a host by:
      - i. Randomly select one host that can be associated with two or more APs.
      - ii. Randomly select one AP that is not currently associated but can be newly associated with the host.
    - (b) Otherwise, swap the assigned APs between two AP locations by:
      - i. Randomly select one AP location.
      - ii. Randomly select another AP location that is assigned an AP with the different type.
      - iii. Swap the assigned APs between the two AP locations.
  3. Calculate the cost function  $E^{new}$  for this neighbor solution and the increase of the cost function  $\Delta E = E^{new} - E$  if the new solution is accepted.

4. If  $\Delta E \leq 0$  or  $rand1 \leq \exp\left(-\frac{\Delta E}{Tp}\right)$ , accept the neighbor solution as the new solution, where  $rand1$  returns a 0 – 1 random number. Otherwise, discard it.
5. If  $E^{new} < E_{best}$ , update  $S_{best}$  and  $E_{best}$ . Otherwise, increment  $L_{cnt}$  by 1.
6. If  $I_{cnt} = RN$ , output  $S_{best}$  and terminate the algorithm. Otherwise, increment  $I_{cnt}$  by 1 and go to 2.

## 3 Channel Assignment Extension

In this section, we present the channel assignment extension for the holding AP assignment algorithm.

### 3.1 Importance of Channel Assignment

The IEEE802.11 standards allow the use of 2.4 GHz and 5 GHz bands with plural channels. Namely, the maximum of 13 channels in Japan are available for 2.4 GHz, and 19 channels for 5 GHz. The channels for 5 GHz can be used at the same time without interferences. However, for the more popular 2.4 GHz, the allocated frequencies of the adjacent channels are partially overlapped so that the interferences can occur if they are used at the same time in the close locations. Actually, only four channels can be used without interference.

In addition, if the *channel bonding* is used for 11n or 11ac, the number of non-overlapping channels further reduced because plural adjacent channels are used together as one channel. Deek et al. (2014); W. Wang et al. (2016); K. Hanada et al. (2013). Thus, the proper channel assignment to the APs is very important in designing high performance WLANs. In this section, we extend the holding AP assignment algorithm to consider the optimal channel assignment.

### 3.2 Formulation of Channel Assignment Extension

The channel assignment extension of the holding AP assignment algorithm is formulated as follows:

- Inputs:
  - the holding AP assignment result: the type and connected hosts for each AP location
  - $|c|$ : the number of available non-overlapping channels
  - $RN_{ch}$ : the number of iterations ( $RN_{ch} = 1000$  in the paper)
  - $Tp_{ch}$ : the SA temperature ( $Tp_{ch} = 2.5$ )
  - $d_w$ : the interference range ( $d_w = 100$ ).
- Outputs:  $c_i$ : the assigned channel to  $La_i$ .

- Objective: to minimize the following cost function  $E_{ch}$ :

$$E_{ch} = C \sum_i IT_i + D \max_i [IT_i] \quad (4)$$

$$IT_i = \sum_{\substack{k \in I_i \\ c_k = c_i}} T_k \quad (5)$$

where  $IT_i$  represents the *interference-aware communication time* for  $La_i$ ,  $T_i$  does the *communication time* for  $La_i$ ,  $I_i$  does the set of the APs that can be interfered with  $La_i$ ,  $C$  and  $D$  do constant coefficients ( $C = 1$ ,  $D = 4$  in this paper). This cost function intends the minimization of the load of the overall network and the load of the bottleneck AP.

### 3.3 Channel Assignment Procedure

The channel assignment extension consists of three steps.

#### 3.3.1 AP Interference Graph

In the first step, the *AP interference graph* ( $G_{AP}$ ) is generated to describe the radio interferences among the APs. Each vertex in  $G_{AP}$  represents an AP and each edge does the interference between two end APs. In this paper, when two APs are located within the interference range  $d_w$ , the edge is generated, where the signal attenuations by obstacles between them is considered.

#### 3.3.2 Initial Solution by Greedy Method

The initial solution is constructed by assigning channels to the APs sequentially in descending order of the loads.

1. Calculate the communication time of each AP without considering the interferences from other APs by:

$$T_i = \sum_j \frac{1}{sp_{ij}} \quad (6)$$

where  $T_i$  represents the communication time for  $La_i$  and  $sp_{ij}$  does the link speed between  $La_i$  and host  $j$ .

2. Calculate the *adjacent communication time* for each AP by:

$$NT_i = \sum_{e(i,k) \in G_{AP}} T_k \quad (7)$$

where  $NT_i$  represents the adjacent communication time for  $La_i$  and  $e(i,k)$  represents the edge between  $La_i$  and  $La_k$ .

3. Sort the APs in descending order of  $NT_i$  where the tiebreak is resolved by  $T_i$ .

4. Generate the set of the interfered APs for each AP by:

(a) Initialize the interfered AP set  $I_i$  for  $La_i$  by  $La_i$  itself:  $I_i = \{i\}$ .

(b) Add the AP that is interfered with every AP in the current  $I_i$  into  $I_i$  in the sorted order.

5. Calculate the *interference communication time* for  $La_i$  by:

$$AT_i = \sum_{k \in I_i} T_k \quad (8)$$

where  $AT_i$  represents the interference communication time for  $La_i$ .

6. Sort the APs in descending order of  $AT_i$  where the tiebreak is resolved by  $NT_i$ .

7. Assign one channel to each AP in the sorted order such that the following *channel communication time* is minimized:

$$IT_{ic} = \sum_{\substack{k \in I_i \\ c_k = c}} T_k \quad (9)$$

where  $IT_{ic}$  represents the channel communication time for  $La_i$  with channel  $c$ . It is noted that one channel for each of 2.4 GHz and 5.0 GHz must be assigned here if the AP can use both bands.

8. Save the initial solution as the best solution  $S_{best}$  and the initial cost  $E_{ch}$  as the best cost  $E_{best}$ .

#### 3.3.3 Solution Improvement by SA

As in the holding AP assignment, the initial solution is improved by SA.

1. Initialize the iteration counter  $I_{cnt}$  by 0.
2. Randomly select one AP to change its assigned channel.
3. Randomly select a new channel to the AP.
4. Calculate the new cost function  $E_{ch}^{new}$  for this channel assignment and the cost function increase by  $\Delta E_{ch} = E_{ch}^{new} - E_{ch}$ .
5. If  $\Delta E_{ch} \leq 0$  or  $rand1 \leq \exp(-\frac{\Delta E_{ch}}{T_{pch}})$ , accept the new channel. Otherwise, discard it.
6. If  $E_{ch}^{new} < E_{best}$ , update the best solution  $S_{best}$ .
7. If  $I_{cnt} = RN_{ch}$ , output  $S_{best}$  and terminate the algorithm. Otherwise, increment  $I_{cnt}$  by 1 and go to 2.

## 4 Model for Partially Overlapping Channel

In this section, we present a simple model to estimate the link speed drop or the communication time increase caused by the interferences in partially overlapping channels.

### 4.1 Interference Degree

For this model, the *interference degree* between two adjacent APs is defined to estimate the communication time increase of each incident link to them. Actually, it is represented by the *channel interference degree* that is given by the difference between the channels assigned to the APs, and *distance interference degree* that is given by the physical distance between the AP locations.

#### 4.1.1 Channel Interference Degree

In K. Zhou et al. (2014), Zhou et al. presented the *channel interference degree* between two IEEE802.11n links using the 20 MHz channel width without the *channel bonding*. Because our paper considers the 40 MHz channel width by the channel bonding, we extended their channel interference degrees by taking the average of the degrees for two adjacent 20 MHz channels. For example, when the channel difference is 1, one 20 MHz channel among the bonded 40 MHz channel is partially overlapped by the adjacent 20 MHz channel, and another one is fully overlapped. Thus, in this case, the channel interference degree becomes  $(0.7272 + 1.0)/2 = 0.8636$ , where 0.7272 is given as the degree between the two adjacent 20 MHz channels in K. Zhou et al. (2014). Table 2 shows the channel interference degree for each channel difference. When the channel difference is 0, it becomes the largest 1, and when it is larger than 8, it becomes 0. Then, our model assumes that the communication time of a link is proportionally increased by this degree.

#### 4.1.2 Distance Interference Degree

The distance interference degree is decreased proportionally to the physical distance  $d$  between the locations of the APs, as shown in the following equation:

$$f(d) = \max(0, 1 - d/d_w) \quad (10)$$

where  $d_w$  represents the maximum range of the interference, where  $d_w = 100$  is used in this paper.

### 4.2 Communication Time Amendment by Interference Degree

The communication time  $T_i$  of  $AP_i$  should be amended to reflect the interferences from the APs within its interference range. The interference degree  $id_{ik}$  of  $AP_i$  from  $AP_k$  is calculated by the multiplication of the channel interference degree  $cd_{ik}$  and the distance interference degree  $dd_{ik}$ . It is noted that  $cd_{ik}$  can be

obtained from Table 2 by considering the difference between the assigned channels, and  $dd_{ik}$  can be from Eq. (10) using the physical distance between their locations. Our model assumes that the communication time is proportionally increased by the summation of the interference degrees from its interfered APs:

$$id_k = cd_{ik} \times dd_{ik} \\ T_i^{int} = T_i \times \left( 1 + \sum_{k \neq i} id_{ik} \right) \quad (11)$$

where  $T_i^{int}$  represents the *amended communication time* of  $La_i$  by the interferences from other APs.

In the channel assignment extension in Section 3, this amended communication time is used to calculate the new cost function  $E_{ch}^{new}$  in the solution improvement by SA in Section 3.3.3, where all the APs are assigned channels, and the interference degrees among them can be calculated.

### 4.3 Discussion of Interference Model under Partially Overlapping Channels

Here, we discuss related studies on the interference model under partially overlapping channels. In A. B. M. Alim Al Islam et al. (2016), Islam et al. investigated the channel assignment method in wireless mesh networks where each node has multiple wireless communication interfaces. In J. Wang et al. (2016), Wang et al. proposed the assignment method of end-to-end channels assignment using partially overlapping channels for wireless mesh networks. They referred the work in A. Mishra et al. (2006) for partially overlapping channels. In P. B. F. Duarte et al. (2012), Duarte et al. proposed the channel assignment algorithm for wireless mesh networks using the game theory. In Y. Ding et al. (2012), Ding et al. proposed the genetic algorithm to improve the throughput using partially overlapping channels. In B. Jaumard et al. (2016), Jaumard et al. studied throughput improvements and delay reductions in wireless mesh networks using partially overlapping channels. In W. Zhao et al. (2014), Zhao et al. proposed the algorithm for allocating APs and assigning partially overlapping channels using the mixed integer linear programming (MILP) for wireless networks. In W. Zhao et al. (2016), Zhao et al. also proposed the algorithm for allocating AP densities and assigning partially overlapping channels. In J. H. Wang et al. (2015), Wang et al. proposed the channel assign algorithm using partially overlapping channels for multi-channel multi-radio wireless mesh networks.

Among them, the studies in J. Wang et al. (2016), A. Mishra et al. (2006), B. Jaumard et al. (2016), and J. H. Wang et al. (2015) determine the interference degree by calculating the signal strength. The studies in P. B. F. Duarte et al. (2012) and Y. Ding et al. (2012) use measurement results. Their results show that interference degrees are different from each other.

**Table 2** Channel interference degree (40 MHz).

channel difference	0	1	2	3	4	5	6	7	8
interference degree	1	0.8636	0.6357	0.51875	0.5027	0.364	0.1358	0.01875	0.0027

**Table 3** Types and numbers of holding APs and hosts in three instances.

instance	AP: type(number)	host: type(number)
1	7(5), 4(5)	50: 7(25), 4(25) 75: 7(38), 4(37) 100: 7(50), 4(50)
2	4(5), 3(5)	50: 4(25), 3(25) 75: 4(38), 3(37) 100: 4(50), 3(50)
3	8(2), 7(2), 6(1), 5(2), 4(2), 3(1)	50: 7(25), 4(25) 75: 7(38), 4(37) 100: 7(50), 4(50)

## 5 Evaluations by Simulations

In this section, we evaluate our proposal through simulations using the WIMNET simulator N. Funabiki et al. (2011), in both cases with/without partially overlapping channels.

### 5.1 Case without Partially Overlapping Channels

First, we evaluate the proposed algorithm for simple cases without using partially overlapping channels.

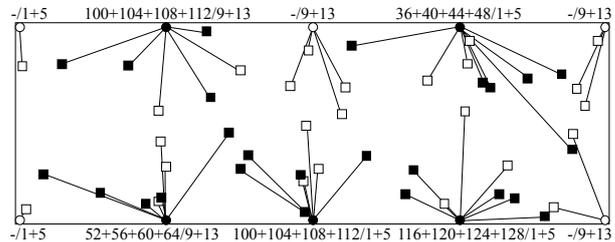
#### 5.1.1 Simulation Instances

In the simulation instances, the square plain field of  $150\text{ m} \times 50\text{ m}$  is used, where 10 AP locations are selected along the boundary with the same interval, and 50, 75, or 100 hosts are distributed randomly. Table 3 summarizes the types of APs and the hosts with their numbers. As the number of non-overlapping channels, four is used for 5.0 GHz and two is for 2.4 GHz. The standard link speed  $sd_{ij}$  for any pair of an AP and a host is calculated from their coordinates and the link speed estimation equation in N. Funabiki et al. (2012).

#### 5.1.2 Algorithm Result for instance 1

In Figure 2, the type-4 AP is connected with only type-4 hosts and the type-7 AP is with type-4 or type-7 hosts. The number of associated hosts for the type-4 AP is three or less, and that for the type-7 AP is between six and nine. As the result, the communication time for the AP exists between 0.006 and 0.029. This result indicates that the AP assignment and host association result by the algorithm does not only satisfy the constraints but also avoids the bottleneck AP.

In Figure 2, the type-4 AP is connected with only type-4 hosts and the type-7 AP is with type-4 or type-7 hosts. The number of associated hosts for the type-4 AP is three or less, and that for the type-7 AP is between six and nine. As the result, the communication time for the

**Figure 2** AP and channel assignment result for instance 1.

AP exists between 0.006 and 0.029. This result indicates that the AP assignment and host association result by the algorithm does not only satisfy the constraints but also avoids the bottleneck AP.

#### 5.1.3 Throughput Results

Table 4 show the throughput results for the three instances using the WIMNET simulator. Here, the four cases for the holding AP and channel assignments are considered:

- 1) AP/channel assignment by proposed algorithm using four channels for 5.0 GHz and two channels for 2.4 GHz (proposal),
- 2) AP assignment by congestion order using one channel (compare 1),
- 3) AP assignment by proposed algorithm using one channel (compare 2),
- 4) AP assignment by proposed algorithm and random channel assignment using four channels for 5.0 GHz and two channels for 2.4 GHz (compare 3).

In 2), the APs are sorted in descending order of the number of the nearest hosts, and the holding APs are assigned there in this order from the highest performance ones.

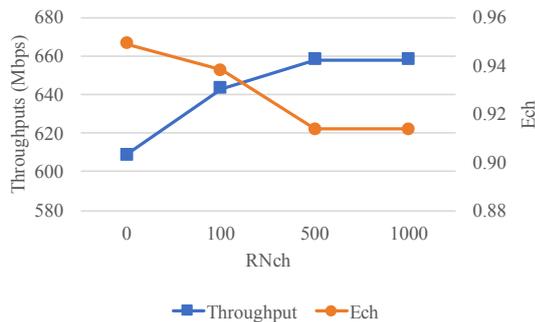
Table 4 show that the throughput for compare 2 is about 1.1 times higher than that for compare 1. It indicates that the AP assignment in the proposed algorithm can improve the holding AP assignment. Besides, they show that the throughput for proposal is about 1.3 times higher than that for compare 3.

#### 5.1.4 Convergence of SA for Channel Assignment Extension

In this subsection, we investigated the convergence of SA for the channel assignment extension to better network solutions. Figure 3 shows the value of the cost function  $E_{ch}$  and the simulated throughput (Mbps) of the final

**Table 4** Throughput results.

instance	# of hosts	throughput (Mbps)			
		proposal	compare1	compare2	compare3
1	50	658.10	272.90	295.80	521.57
	75	615.07	244.10	294.78	471.83
	100	569.25	243.11	268.25	414.92
2	50	181.10	95.49	97.24	120.32
	75	200.82	96.67	97.68	170.39
	100	181.21	92.03	96.80	145.35
3	50	656.06	245.54	298.85	482.60
	75	618.42	223.19	293.29	480.58
	100	544.39	212.72	265.87	466.26

**Figure 3** Relationship  $E_{ch}$  and throughput for *instance 1*, 50 hosts.

solution by SA for *instance 1* with 50 hosts, when the number of iterations  $RN_{ch}$  is set 0, 100, 500, and 1000. It indicates that  $E_{ch}$  decreases and the throughput increases until  $RN_{ch} = 500$ . Thus, the convergence of SA to better solutions with smaller values of  $E_{ch}$  indicates the convergence of the network to better performances with higher throughputs.

## 5.2 Case with Partially Overlapping Channels

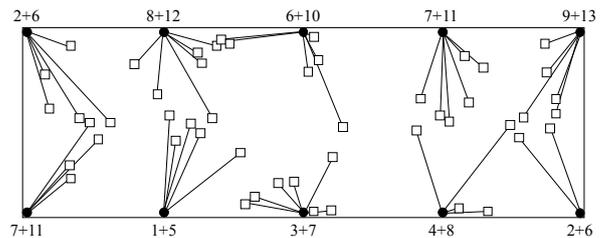
Next, we evaluate the proposed algorithm for more realistic cases using partially overlapping channels. For simulations by the WIMNET simulator, the following amended link speed is used for the link speed:

$$sp_{ij}^{int} = sp_{ij} / (1 + \sum_{\substack{k \\ k \neq i}} id_{ik}) \quad (12)$$

where  $sp_{ij}^{int}$  represents the amended link speed of each link incident to  $AP_i$  by the interferences from other APs.

### 5.2.1 Simulation Instances

In the simulated instances, the square plain field of  $150\text{ m} \times 50\text{ m}$  for *instance 4*, the field of  $75\text{ m} \times 25\text{ m}$  for *instance 5* as the half size of *instance 4*, and the field of  $300\text{ m} \times 100\text{ m}$  for *instance 6* as the double size, are used. In each field, 10 AP locations are selected with the same interval along the top and bottom boundaries, and 50 hosts are randomly allocated. For simplicity, all the

**Figure 4** Algorithm result for *instance 4*.**Table 5** Throughput results using eight partially overlapping channels.

instance	throughput (Mbps)	
	proposal	compare
4	156.63	66.79
5	98.46	41.81
6	270.33	203.92

APs have type 4 (11n and two antennas), and all the hosts have type 3 (11n and one antenna). To avoid the bias in random numbers, five trials are repeated for each instance using different seeds, and their average results are used in evaluations.

### 5.2.2 Algorithm Results

Figure 4 illustrates the channel assignment result using partially overlapping channels for *instance 4*. The channel bonding is adopted here. The black circle represents an AP and the white square does a host. This figure shows that each AP is associated with the similar number of hosts in order to average the loads among them. Besides, among 13 channels, eight bonding channels of 1 + 5, 2 + 6, 3 + 7, 4 + 8, 6 + 10, 7 + 11, 8 + 12, and 9 + 13 are used here.

### 5.2.3 Throughput Results

Table 5 shows the total throughput results by the proposed algorithm using three partially overlapping channels for the three instances. For the comparison, the results using two non-overlapping channels of 1 + 5 and 9 + 13 are also shown there.

**Table 6** Throughput results for reference cases.

instance	throughput (Mbps)				
	R=1.1	R=1.2	R=1.3	R=1.4	R=1.5
4	139.15	125.39	115.57	106.73	99.64
5	84.58	74.31	67.61	62.62	58.76
6	255.04	240.85	228.40	216.35	204.96

Table 5 indicates that the proposal improves the throughput by 2.4 times for *instance 4*, by 2.4 times for *instance 5*, and by 1.3 times for *instance 6* from the comparison, which confirms the effectiveness of using partially overlapping channels in the proposal. Particularly, the improvement is largest for *instance 5* that has the smallest field. In this instance, since every AP is located within the interference range, only two APs assigned different channels can communicate at the same time in the comparison. On the other hand, three APs can communicate at the same time in the proposal, although the link speed is decreased by the interference. These results suggest that the use of partially overlapping channels is more effective in congested fields with a lot of APs.

### 5.3 Effect of Interference Model Accuracy

In this subsection, we discuss the effect of the accuracy of the *interference model* under *partially overlapping channels* to the throughput performance of the network. This model considers the *channel interference degree* and the *distance interference degree* to estimate the link speed drop by interferences from other links under partially overlapping channels. In this subsection, we prepare a *reference case* where both the degrees are increased by  $R$  times and are saturated by 1.0. The three cases of  $R = 1.1, 1.2, 1.3, 1.4,$  and  $1.5$  are examined. Table 6 shows the throughput results for these three reference cases.

The results in Table 6 are better than the throughput results in “compare” in Table 5 in any instance. It indicates that our proposal with the interference model under partially overlapping channels can improve the throughput performance of the network, even if the model accuracy is not sufficient. The accuracy investigation will be in future works.

## 6 Conclusion

This paper defines the holding access-point (AP) assignment problem as a new optimization one for designing high-performance wireless local-area networks and presents its two-phase heuristic algorithm. The channel assignment extension to the APs using partially overlapping channels is also presented with the model for estimating the link speed drop by interferences. The effectiveness of our proposal is verified through simulations in six instances with and without partially overlapping channels. In future works, the performance

of our proposal will be evaluated in a variety of simulation instances that have non-uniform host distributions and consider indoor environments.

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