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 optimisation 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 minimised, 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; WLAN; holding access-point; partially overlapping channel; assignment algorithm; combinatorial optimisation problem.

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1 Introduction

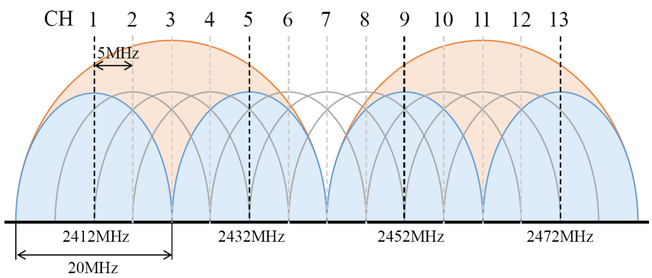
Recently, new *access-point* (*AP*) devices providing higher performances and advanced functions have become available within short time for *wireless local-area networks* (WLANs), due to the rapid developments of the technologies for device manufacturing, wireless communications, and supporting software. As a result, many organisations 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 multiple-input-multiple-output (MIMO) 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 realising plural streams between the source and destination nodes using multiple antennas (Perahia and Stacey, 2008; Gast, 2013; Nee, 2011; Bejarano et al., 2013; Spencer et al., 2004; Hiraguri and Nishimori, 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 are available. Actually, in Japan, only 13 channels can be used for 2.4 GHz bands, and 19 channels can be for 5 GHz bands, when 20 MHz 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 2.4 GHz (see online version for colours)



In this paper, first, we define the *holding AP assignment problem* as a new combinatorial optimisation 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 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 initialisation phase and the local search optimisation 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 minimised, 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 organised 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 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.

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	1,300

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 analysed using the measurement results of the devices with this type, and is well modelled. 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 optimisation 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 minimise the cost function E in equation (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 equation (2):

$$sa_{ij} = sd_{ij}\frac{\min\left(m_{ati}, m_{htj}\right)}{m_K} \quad (2)$$

where sd_{ij} represents the standard link speed between La_i and Lh_j, m_{ati} and m_{htj} 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

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:

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

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 sorts 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 equation (2).

8 Calculate the cost function E in equation (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} = 10,000 in the paper)

RN the number of iterations (*RN* = 8,000,000)

Tp the SA temperature (*Tp* = 0.00013).

1 Initialise the iteration counter I_{cnt} and the local minimum counter L_{cnt} by 0.

2 Generate a neighbour solution from the current one.

   a If $L_{cnt} < L_{max}$, change the associated AP of a host by:

   - Randomly select one host that can be associated with two or more APs.
   - 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:

   - Randomly select one AP location.
   - Randomly select another AP location that is assigned an AP with the different type.
   - Swap the assigned APs between the two AP locations.

3 Calculate the cost function E^{new} for this neighbour 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 $rand1 \leq \exp\left(-\frac{\Delta E}{T_p}\right)$, accept the neighbour solution as the new solution, where *rand*1 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; Wang et al., 2016; 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:

   1 the holding AP assignment result: the type and connected hosts for each AP location

2. $|c|$: the number of available non-overlapping channels
3. RN_{ch}: the number of iterations (RN_{ch} = 1,000 in the paper)
4. Tp_{ch}: the SA temperature (Tp_{ch} = 2.5)
5. d_w: the interference range (d_w = 100).

- Outputs: c_i: the assigned channel to La_i.
- Objective: to minimise the following cost function E_{ch}:

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

$$IT_i = \sum_{\substack{k\in I_i \\ c_k = c_i}} T_k \tag{5}$$

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 minimisation 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:

$$T_i = \sum_j \frac{1}{sp_{ij}} \tag{6}$$

   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:

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

   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. Initialise 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:

$$AT_i = \sum_{k\in I_i} T_k \tag{8}$$

   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 minimised:

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

   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. Initialise 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 $\Delta E_{ch} \le 0$ or $rand1 \le \exp\left(-\frac{\Delta E_{ch}}{Tp_{ch}}\right)$, 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

Zhou et al. (2014) 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 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:

$$f(d) = \max\left(0, 1 - d / d_w\right) \tag{10}$$

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 equation (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:

$$id_k = cd_{ik} \times dd_{ik}$$

$$T_i^{int} = T_i \times \left(1 + \sum_{k \neq 1} id_{ik}\right) \tag{11}$$

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. Alim Al Islam et al. (2016) investigated the channel assignment method in wireless mesh networks where each node has multiple wireless communication interfaces. Wang and Shi (2016), proposed the assignment method of end-to-end channels assignment using partially overlapping channels for wireless mesh networks. They referred the work in Mishra et al. (2006) for partially overlapping channels. Duarte et al. (2012) proposed the channel assignment algorithm for wireless mesh networks using the game theory. Ding et al. (2012) proposed the genetic algorithm to improve the throughput using partially overlapping channels. Jaumard et al. (2016) studied throughput improvements and delay reductions in wireless mesh networks using partially overlapping channels. Zhao et al. (2014) proposed the algorithm for allocating APs and assigning partially overlapping channels using the mixed integer liner programming (MILP) for wireless networks. Zhao et al. (2016) also proposed the algorithm for allocating AP densities and assigning partially overlapping channels. Wang et al. (2015) proposed the channel assign algorithm using partially overlapping channels for multi-channel multi-radio wireless mesh networks.

Among them, the studies in Wang and Shi (2016), Mishra et al. (2006), Jaumard et al. (2016), and Wang et al. (2015) determine the interference degree by calculating the signal strength. The studies in Duarte et al. (2012) and 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 Funabiki (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.

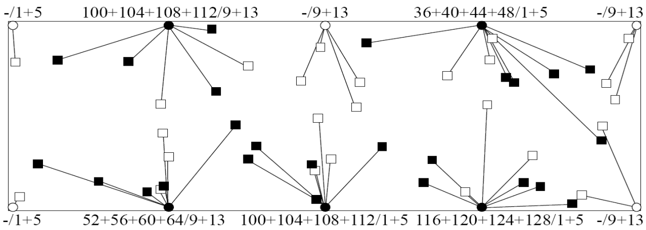
5.1.1 Simulation instances

In the simulation instances, the square plain field of 150 m × 50 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 summarises 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 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.

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



5.1.3 Throughput results

Table 4 shows 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 shows 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.

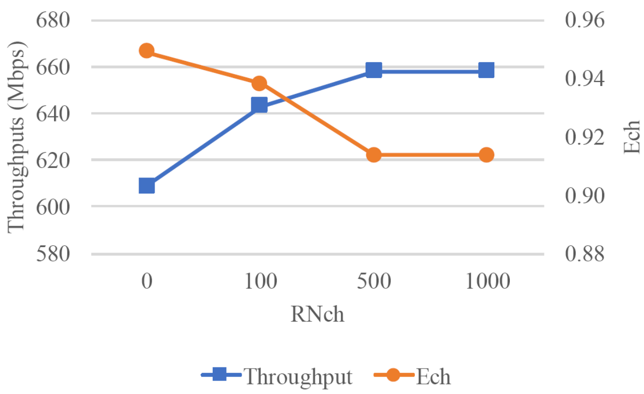
5.1.4 Convergence of SA for channel assignment extension

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 solution by SA for *instance* 1 with 50 hosts, when the number of iterations RN_{ch} is set 0, 100, 500, and 1,000. 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.

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* (see online version for colours)



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:

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

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 m × 50 m for instance 4, the field of 75 m × 25 m for instance 5 as the half size of instance 4, and the field of 300 m × 100 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 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 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

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.

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

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 Conclusions

This paper defines the holding access-point (AP) assignment problem as a new optimisation one for designing high-performance WLANs 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.

References

Alim Al Islam, A.B.M., Islam, M.J., Nurain, N. and Raghunathan, V. (2016) 'Channel assignment techniques for multi-radio wireless mesh networks: a survey', *IEEE Commun. Surveys & Tutorials*, Vol. 18, No. 2, pp.988–1017.

Bejarano, O., Knightly, E.W. and Park, M. (2013) 'IEEE 802.11ac: from channelization to multi-user MIMO', *IEEE Commun. Magazine*, October, Vol. 51, No. 10, pp.84–90.

Cisco Systems, Inc. (2016) *Enterprise Mobility 8.1 Design Guide*, November [online] http://www.cisco.com/c/en/us/td/docs/wireless/controller/8-1/Enterprise-Mobility-8-1-Design-Guide/Enterprise_Mobility_8-1_Deployment_Guide.html (accessed 1 April 2017).

Deek, L., Garcia-Villegas, E., Belding, E., Lee, S.J. and Almeroth, K. (2014) 'Intelligent channel bonding in 802.11n WLANs', *IEEE Trans. on Mobile Compu.*, June, Vol. 13, No. 6, pp.1242–1255.

Ding, Y., Huang, Y., Zeng, G. and Xiao, L. (2012) 'Using partially overlapping channels to improve throughput in wireless mesh networks', *IEEE Trans. Mobile Comput.*, November, Vol. 11, No. 11, pp.1720–1733.

Duarte, P.B.F., Fadlullah, Z.M., Vasilakos, A.V. and Kato, N. (2012) 'On the partially overlapped channel assignment on wireless mesh network backbone: a game theoretic approach', *IEEE J. Sel. Area. Commu.*, January, Vol. 30, No. 1, pp.119–127.

Funabiki, N. (Ed.) (2011) *Wireless Mesh Networks*, InTech, Open Access Publisher [online] https://www.intechopen.com/books/editor/wireless-mesh-networks.

Funabiki, N., Maruyama, W., Nakanishi, T. and Watanabe, K. (2012) 'An extension of routing tree algorithm considering link speed change in IEEE 802.11n protocol for wireless mesh network', *Proc. MENS2012*, September, pp.600–605.

Gast, M. (2013) *802.11ac: A Survival Guide*, O'Reilly Media, July [online] http://chimera.labs.oreilly.com/books/1234000001739/index.html (accessed 1 April 2017).

Hanada, K., Yamamoto, K., Morikura, M., Ishihara, K. and Kudo, R. (2013) 'Game-theoretic analysis of multibandwidth channel selection by coordinated APs in WLANs', *IEICE Trans. on Commun.*, June, Vol. E96-B, No. 6, pp.1277–1287.

Hiraguri, T. and Nishimori, K. (2015) 'Survey of transmission methods and efficiency using MIMO technologies for wireless LAN Systems', *IEICE Trans. Commun.*, July, Vol. E98-B, No. 7, pp.1250–1267.

Jaumard, B., Negahishirazi, M. and Kaddour, M. (2016) 'Increased throughput and reduced delay with partially overlapping channel in WMNs', *Proc. Elect. Comp. Eng.*, May, pp.1–6.

Mishra, A., Shrivastava, V., Banerjee, S. and Arbaugh, W. (2006) 'Partially overlapped channels not considered harmful,' *ACM SIGMETRICS Perform. Eva. Review*, Vol. 34, No. 1, pp.63–74.

Nee, R.V. (2011) 'Breaking the gigabit-per-second barrier with 802.11ac', *IEEE Wireless Commun.*, April, Vol. 18, No. 2, p.4.

Perahia, E. and Stacey, R. (2008) *Next Generation Wireless LANs: Throughput, Robustness, and Reliability in 802.11n*, Cambridge Univiversity Press, Cambridge, August.

Spencer, Q.H., Peel, C.B., Swindlehurst, A.L. and Haardt, M. (2004) 'An introduction to the multi-user MIMO downlink', *IEEE Commun. Magazine*, October, Vol. 42, No. 10, pp.60–67.

Wang, J. and Shi, W. (2016) 'Partially overlapped channels- and flow-based end-to-end channel assignment for multi-radio multi-channel wireless mesh networks', *China Commun.*, April, Vol. 13, No. 4, pp.1–13.

Wang, J.H., Shi, W.X., Cui, K.Q., Jin, Fe. and Li, Y.X. (2015) 'Partially overlapped channel assignment for multi-channel multi-radio wireless mesh networks', *Eurasip J. on Wireless Commun. and Netw.*, December, No. 1, p.25.

Wang, W., Zhang, F. and Zhang, Q. (2016) 'Managing channel bonding with clear channel assessment in 802.11 networks', *Proc. IEEE Int. Conf. on Commun.* (*ICC*), May, p.1–6.

Zhao, W., Fadlullah, Z., Nishiyama, H., Kato, N. and Hamaguchi, K. (2014) 'On joint optimal placement of access points and partially overlapping channel assignment for wireless networks', *Proc. Global Commun. Conf.*, December, pp.4922–4927.

Zhao, W., Nishiyama, H., Fadlullah, Z., Kato, N. and Hamaguchi, K. (2016) 'DAPA: capacity optimization in wireless networks through a combined design of density of access points and partially overlapped channel allocation', *IEEE Trans. Veh. Technol.*, May, Vol. 65, No. 5, pp.3715–3722.

Zhou, K., Jia, X., Chang, Y. and Tang, X. (2014) 'Partially overlapping channel assignment for WLANs using SINR interference model', *Int. J. Commun. Syst.*, November, Vol. 27, No. 11, pp.3082–3095.