A Throughput Drop Estimation Model for Concurrent Communications under Partially Overlapping Channels without Channel Bonding and Its Application to Channel Assignment in IEEE 802.11n WLAN

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SUMMARY Currently, the IEEE 802.11n wireless local-area network (WLAN) has been extensively deployed world-wide. For the efficient channel assignment to access-points (APs) from the limited number of partially overlapping channels (POCs) at 2.4GHz band, we have studied the throughput drop estimation model for concurrently communicating links using the channel bonding (CB). However, non-CB links should be used in dense WLANs, since the CB links often reduce the transmission capacity due to high interferences from other links. In this paper, we examine the throughput drop estimation model for concurrently communicating links without using the CB in 802.11n WLAN, and its application to the POC assignment to the APs. First, we verify the model accuracy through experiments in two network fields. The results show that the average error assignment to the APs is 9.946% and 6.285% for the high and low interference case respectively. The average error assignment to the APs using the throughput drop estimation model for concurrently communicating links using the channel bonding (CB) is 5.946% and 3.285% for the high and low interference case respectively.

1. Introduction

Nowadays, the IEEE 802.11 wireless local-area network (WLAN) has been world-wide deployed as the Internet access network, due to its advantages of the flexibility, the lower cost, and the high data transmission capacity [1], [2]. The IEEE 802.11 WLAN can operate in two unlicensed frequency bands [3], where the 2.4GHz Industrial, Scientific, and Medical (ISM) band is generally adopted, because it provides a wide coverage range with the stronger penetration capability for indoor environments [4]. At both bands, the IEEE 802.11 standards define the limited number of channels for use. One channel basically has the 20MHz width, and the frequency gap between two adjacent channels is merely 5 MHz. Thus, the spectrums of adjacent channels are partially overlapped with each other, which names the partially overlapping channels (POCs). Figure 1 illustrates the 13 POCs in IEEE 802.11n defined in 2.4GHz band. For example, channel 1 partially overlaps with three channels 2, 3, and 4.

To provide seamless connections to the Internet and support a number of users in a wide area, WLANs are often deployed densely using plenty of access points (APs) [5]. Since the number of available channels is limited, each WLAN may confront multiple cross-technology interferences from co-located other WLANs, blue-tooth, microwaves, or sensor devices. Thus, one key challenge in enhancing the throughput performance is to optimize the channel (POC) assignment to each AP in the WLAN, considering the throughput drop by the interferences.

Previously, we studied the throughput drop estimation model for concurrent communications of multiple links adopting the channel bonding (CB) [6], [7]. In the CB, two adjacent 20MHz channels are combined to form one 40MHz channel, to increase the data transmission capacity [8], [9]. This model estimates the throughput drop of the target CB link, which is caused by the interfered CB links, considering the channel distance and the interfered received signal strength (RSSi) at the target AP from the neighbouring interfered APs.

To obtain the nominal throughput of the target link under multiple interfered links, the throughput under no interference is estimated using the throughput estimation model

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Fig. 1 20MHz POCs at 2.4 GHz band.
in [10]. Then, it is subtracted with the throughput drop estimated for each of the interfered links sequentially, in descending order of the throughput drop magnitude.

The CB is one of the key technologies to enhance the data transmission speed in wireless communications. However, it reduces the number of non-interfered channels. Besides, as shown in [11], the wider bandwidth of the CB link can cause the reduction of signal to interference plus noise ratio (SINR) at the distant host from the AP. Then, the lower SINR can cause the adoption of the slower modulation and coding scheme (MCS) and the hidden terminal problem, which can further lower the throughput. Therefore, the conventional non-CB link with 20MHz width is still common in numerous WLANs. Especially, the non-CB link should be used in a dense WLAN, since the CB link cannot provide the designed capacity due to high interferences from other links.

In this paper, we present the throughput drop estimation model for concurrently communicating non-CB links, based on our previous studies. The parameters of the model are newly adjusted based on extensive measurement results for the non-CB links in two network fields, under various conditions of the channel distance and the AP/host locations. Then, the model will be applied to the POC assignment at APs, to prove the effectiveness of the proposed model.

The accuracy of the proposed throughput drop estimation model is verified through experiments in two network fields, where the estimated throughput by the model well matches with the measured one for any case. Then, the effectiveness of the POC assignment at APs using the model is confirmed through experiments in two network topologies and simulations in three network topologies, where the POC assignment using the large number of POCs provides the highest total throughput of the network.

The rest of this paper is organized as follows: Sect. 2 reviews related works in literature. Sections 3 reviews our previous works related to this paper. Section 4 presents the throughput drop estimation model without the CB. Section 5 evaluates the accuracy of the model. Section 6 illustrates the application of the model to the POC assignment. Section 7 concludes this paper with future works.

2. Related Works

In this section, we survey related works in the literature to this paper. A significant amount of research works has addressed the problem of interferences in WLAN to enhance the throughput performance through the channel assignment with/without POCs [12], [13].

In [13], Mishra et al. showed that the orthogonal channel (OC) assignment to APs in WLAN can be inefficient in a network field, if a substantial number of APs are co-located. In this case, any AP may exist within interference ranges of other APs due to limited channels.

In [14]–[16], Mishra et al., Feng et al., and Zhang et al. demonstrated that the careful design of the POC allocation to APs in WLAN can improve the performance with the efficient spatial reuse. In [17], Zhao et al. observed that as the spatial reuse increases, the capacity of WLAN can be scaled up with additional APs in the network field, where the expected distance from a user to the associated AP becomes shorter, which results in the higher data transmission speed.

In [18], Zhao et al. showed that the effect of interferences on the network performance depends on the channel separation and the degree of the frequency overlapping among the interfered links. In particular, the simultaneous interferences from two links will bring about the higher performance deterioration than the single interference, but the smaller deterioration than the summation of the individual ones.

In [17], [19], Zhao et al. and Mukherjee et al. considered the sum of the interfering signal powers at the target node, when more than one APs are interfered. Since the MAC protocol lowers the data transmission rate of the target AP, depending on the level of the individual interference, the simple summation of the individual interferences may fail to identify the real value for the interference. In our paper, the individual interference will be examined sequentially from the highest to the smallest.

In [20], Vanhatupa et al. presented the graph coloring approach (GCA) to acquire solutions for the channel assignment. A feasible solution only occurs when available channels can provide a colored graph. Where a colored graph is not possible, this GCA has no qualitative ordering of possible solutions. On the other hand, our proposed model considers all the POCs and evaluates the performance of each channel based on interferences from other channels.

In [13], Mishra et al. presented studies for the weighted GCA where each weight represents the signal to the noise ratio (SINR). Here, the maximization of SINR is the objective function. However in real WLANs, the throughput may not be linearly dependent on SINR. Thus, the throughput should be used as the optimization parameter as in this paper.

In [21], Elwekeil et al. reported a simulation based study on the channel assignment problem, where the objective is defined to minimize the maximum interference at an AP. The model in [22] was adopted to estimate the interference from the channel overlapping, where it assumes that the interference linearly decreases as the channel separation distance increases. Nevertheless, our experiment results show that the interference does not decrease linearly to the channel separation distance.

The logarithm function has been used in interference studies of WLAN. In [23], Kandasamy et al. studied the relationship between the interference metric and the throughput to quantify the effect of the interference on the WLAN performance. In their study, the logarithm function is adopted to estimate the throughput. They show that the estimated values by the logarithm function fits well with the experiment results.

In [24], Yoon et al. and in [25], Kumar et al. investigated the effects of the cross technology interference
between IEEE 802.11 for Wi-Fi and IEEE 802.15.4 for ZigBee. The relationship between the Wi-Fi packet error rate and the interfering RSS follows the logarithmic curve. They claimed that the logarithm function can be applied to model WLAN performance metrics such as the achievable throughput, the SINR, and the bit error rate.

3. Review of Previous Works

In this section, we review our previous works related to this paper: traffic model adopted, throughput estimation model under non-interference, preliminary definitions for the model, and the drop models under CB.

3.1 Traffic Model Adopted

The models in this paper adopt Iperf [26] to generate TCP packets only for the downlink flows. This approach has been commonly used to model the Internet access behaviours of users in a LAN including the WLAN, because users usually download data or information from servers in the Internet to their PCs or smartphones. Jeong et al. in [27], and Kim et al. in [28] have shown that traffics in most wireless multimedia applications are strongly biased toward downlinks (from APs to STAs) compared to uplinks (from STAs to APs). Very short commands (bytes) are transmitted at uplinks, whereas relatively large files (kilobytes/megabytes) are transmitted at downlinks. The authors argued that downlinks should be allocated more bandwidth than uplinks.

Although in a real condition of a WLAN the traffic can be a bidirectional flow where data is transmitted through both the uplink and downlink concurrently, the downlink flow usually carries much more data than the uplink. Therefore, the downlink is dominant in the WLAN, and has the large influence to the user satisfaction under interferences. Based on these observations, the model is designed and the performance is evaluated through the downlink flow only.

3.2 Throughput Estimation Model under Non-Interference

To estimate the throughput of a link under interferences, first, we apply the throughput estimation model for a single link that can estimate the throughput for the link under non-interference. In this model, the receiving signal strength (RSS) at the host is first estimated using the log distance path loss model [29]:

$$RSS_d = P_1 - 10\alpha \log_{10} d - \sum_k n_k W_k$$

(1)

where $RSS_d$ represents RSS (dBm) at the host, $P_1$ does RSS at 1m distance from the AP when no obstacle exists, $\alpha$ does the path loss exponent, $d(m)$ does the Euclidian distance between the AP and the host, $n_k$ does the number of type $k$ obstacles along the path from the AP to the host, and $W_k$ does the signal attenuation factor (dB) for type $k$ obstacle.

Then, the estimated RSS $RSS_d$ is converted to the estimated throughput $tp_{ij}$ using the sigmoid function:

$$tp_{ij} = \frac{a}{1 + e^{-(RSS_d + b) / c}}$$

(2)

where $tp_{ij}$ represents the estimated throughput (Mbps) and $a$, $b$, and $c$ are constant coefficients.

3.3 Preliminary Definition of Three Distances for Model

To describe the throughput drop estimation model under interferences, the channel distance, the physical distance, and the link distance are defined.

3.3.1 Channel Distance

The channel distance ($chD$) of the two links is defined as the minimum channel difference between the channels of the links. For example, when both links are assigned the same channel, $chD$ is 0, they will be fully overlapped. When one link is assigned channel 1 and another link is channel 3, $chD$ is 2. In this case, these channels are overlapped by 50% for 20MHz.

3.3.2 Physical Distance

The physical distance ($phD$) is defined as the Euclidian distance between the two APs of the links. By increasing the physical distance between the links, the interfering signal between them will fade due to the path loss and the absorption by obstacles on the path [30].

3.3.3 Link Distance

The link distance ($lkD$) is defined as the Euclidian distance between the transmitter and the receiver of the link. Since the signal is propagated from the transmitter to the receiver, the longer link distance reduces the RSS at the receiver and can degrade the throughput.

3.4 Drop Model for One Interfered Link under CB

Next, we estimate the throughput drop caused by the interference using the throughput drop estimation model. Here, the model is presented when only one interfered link exists. The model is composed of the logarithm function of the RSS $RSS'$ and the channel distance $chD$ from the interfered link.

$$tpD(RSS', chD) = p(chD) \times \ln(q(chD) + RSS') + r(chD).$$

(3)

where $tpD(RSS', chD)$ indicates the estimated throughput drop (Mbps), and $p(chD)$, $q(chD)$, and $r(chD)$ represent the constants determined by the channel distance $chD$. The physical distance ($phD$) between the two APs is closely related with the RSS ($RSS'$) of the interfering signal at the AP.
in Eq. (3). When $phD$ increases, the corresponding $RSS^s$ decreases, as shown in Eq. (1) where $RSS_d$ represents $RSS^s$ and $d$ does $phD$.

In Table 1, the values of the three constants in the model, $p$, $q$, and $r$, are computed by OriginPro8 [31] from the throughput drop measurement results for each channel distance using the devices and software in Table 2.

| channel distance | $p$  | $q$  | $r$   |
|------------------|------|------|-------|
| 0                | 27   | 88.17| -20   |
| 1                | 27   | 87.36| -20   |
| 2                | 27   | 89.00| -22   |
| 3                | 25   | 94.50| -22   |
| 4                | 33   | 92.00| -56   |
| 5                | 34   | 92.00| -57   |
| 6                | 45   | 91.00| -98   |
| 7                | 45   | 88.00| -100  |
| 8                | 40   | 75.50| -80   |

Table 1: Parameter values of throughput drop estimation model for CB.

4. For the largest interfered link, adjust $tpD_{ij}^{1st}$ by the maximum speed of the AP of the target link, because different APs may have different throughput performances:

$$tpD_{adj}^{1st} = tpD_{ij}^{1st} \times \frac{tpM_{AP}}{140}$$

(4)

where $tpD_{adj}^{1st}$ represents the adjusted throughput drop by the largest interfered link, and $tpM_{AP}$ does the maximum throughput for the AP of the target link. Then, the throughput $tp_{ij}^{1st}$ of the target link after considering the drop by the first interfered link is estimated by:

$$tp_{ij}^{1st} = tp_{ij} - tpD_{adj}^{1st}$$

(5)

5. For the second interfered link, adjust the $tpD_{ij}^{2nd}$ by:

$$tpD_{adj}^{2nd} = tpD_{ij}^{2nd} \times \frac{tpM_{AP} - tpD_{adj}^{1st}}{140}$$

(6)

Then, the throughput $tp_{ij}^{2nd}$ of the target link after considering the drop by the second interfered link is estimated by:

$$tp_{ij}^{2nd} = tp_{ij}^{1st} - tpD_{adj}^{2nd}$$

(7)

6. If more interfered links exist, repeat the same procedure.

4. Throughput Drop Estimation Model for Non-CB Links

In this section, we present the proposed throughput drop estimation model for non-CB links, based on measurement results. First, preliminary measurements are conducted. Then, based on the preliminary measurement results, the model for non-CB is proposed.

4.1 Measurement Setup

The hardware and software in Table 2 are adopted in experiments to compose TCP links between hosts and servers through APs. These devices are set up on the third floor of Engineering Building #2 at Okayama University. The non-CB channel of the first link is fixed at channel 1, and that of the second link is changed from channel 1 to channel 13.

For the throughput measurements, Iperf is adopted as a popular tool for measuring the TCP throughput by generating TCP packets [26]. This software automatically saturates the TCP traffic of the WLAN link.

The frame aggregation in the IEEE 802.11n is used in the experiments. It allows multiple frames to be transmitted in the single block and be acknowledged together over a single channel access. By reducing the overhead induced by the CSMA/CA protocol, it can increase the throughput performance of the IEEE 802.11n over the IEEE 802.11a/b/g without the frame aggregation.

| Parameters       | Values |
|------------------|--------|
| Wireless NIC     | Atheros XSPAN [32] |
| Processor        | Intel Core i5-2520M 2.5 GHz |
| Chipset          | Intel HM65 Express |
| Access Point (all links) | NECT WG2600HP |
| OS               | Ubuntu 14.04 LTS (kernel 3.13.0-57) |
| Processor        | Intel Core i5-2520M 2.54 GHz |
| Chipset          | Intel HM65 Express |
| Wireless NIC     | Atheros AR938x [33] |
| Access Point (link1) | Toshiba dynabook R731/B |
| OS               | Ubuntu 14.04 LTS (kernel 3.13.0-57) |
| Processor        | Intel Core i5-2520M 2.54 GHz |
| Chipset          | Intel HM65 Express |
| Wireless NIC     | Atheros AR938x |
| Access Point (link2) | Fujitsu lifebook S761/C |
| OS               | Ubuntu 14.04 LTS (kernel 4.2.0-27) |
| Processor        | Intel Core i5-2520M 2.5GHz |
| Chipset          | Mobile Intel QM67/Express |
| Wireless NIC     | Atheros XSPAN [34] |

Table 2: Devices and software for measurements with CB.
4.2 TCP Versus UDP Protocols

Currently, the TCP protocol has been used in a lot of important applications such as the Web application system, the file transmission, and the electric mail. In [36], Ryu et al. have demonstrated that the TCP traffics have dominated the current usages of the Internet where more than 90% of the Internet traffics is TCP. In [37], Afanasyev et al. shows that the TCP protocol carries most of the Internet traffics, and the performance of the Internet depends to a great extent on how well TCP traffics work.

On the other hand, the UDP protocol does not adopt the flow control or have the data reception acknowledgement. This makes UDP less reliable since the successful packet delivery cannot be guaranteed. Thus, UDP is less adopted for the Internet access, although it is lighter and can be faster than TCP.

Therefore, the TCP throughput significantly impacts the user experience in the application as well as the network resource utilization, and we have studied the throughput estimation model including the throughput drop estimation model of a WLAN link for TCP traffics.

4.3 Preliminary Throughput Measurement Results

First, we examine the largest channel distance (chD) that can cause the interference between two adjacent links. In the experiments, the link distance (lkD) between a host and an AP is fixed at 0.5m, and the physical distance between the two APs (phD) is at 5m.

From the throughput results of the individual links under interferences, it is discovered that the individual throughput always fluctuates. This may occur, since the contention among the links is not well resolved by the current carrier sense mechanism [38]. It can cause the unfair channel occupancy among them. Thus, we will use the average throughput among them in the evaluations.

Figure 2 shows the average throughput of the two links for a different chD. For chD = 4 or smaller, the average throughput is extremely low due to the high interference [39]. Then, for chD = 5 or larger, it is quickly increasing as the less interference. For chD = 6 or larger, it becomes maximum due to no interference. Therefore, we will assess the throughput drop for chD = 5 or smaller.

Figure 3 shows the changes of the throughput drop of the first link for a different chD. Here, lkD = 0.5m is fixed, and phD is changed from 3m to larger ones to obtain the different interfering RSS.

4.4 Proposed Drop Model for Two Interfered Links

The results in Fig. 3 suggest that again, the natural logarithm function in Eq. (3) can be used to estimate the throughput drop (tpD) for non-CB links.

Then, the parameter values for Eq. (3) in Table 3 are derived from measurement results in Fig. 3.

4.5 Proposed Drop Model for Multiple Interfered Links

Then, the throughput drop estimation model is presented for three or more interfered links. As for CB links, the interfered links are explored sequentially in descending order of their drops. It is noted that only two interfered links are
considered here. If three or more interfered links exist, the same procedure should be repeated.

First, the throughput drop estimations in Eq. (4) and Eq. (6) should be adjusted to consider the difference of the maximum throughput of the APs for non-CB (75Mbps) and CB (140Mbps) as follows:

\[
tpD_{1st\ adj} = tpD_{1st} \times \frac{tpM_{AP}}{75} \tag{8}
\]

\[
tpD_{2nd\ adj} = tpD_{2nd} \times \frac{tpM_{AP} - tpD_{1st\ adj}}{75} \tag{9}
\]

Then, the dropped throughput under the interferences for the target link is obtained by sequentially subtracting the \(tpD_{1st\ adj}\) and \(tpD_{2nd\ adj}\) from \(tpij\), as in Eq. (5) and Eq. (7).

5. Evaluation of Model Estimation Accuracy

In this section, we evaluate the accuracy of the throughput drop estimation model for non-CB links by comparing the estimated throughput results with the measured ones in two network fields.

5.1 Network Topology

Figure 4 illustrates the network topology for throughput measurements. The hardware and software in Table 2 are adopted to compose three TCP links where each TCP link connects a host to a server through an AP.

5.2 Network Fields

The third floor of Engineering Building #2 and the second floor of Graduate School of Natural Science and Technology Building at Okayama University are used as the network fields. Figure 5 shows the floor layouts. In either field, several other WLANs can be observed, which may cause the hidden terminal problem to the target link in our experiments. Fortunately, the signals from them are weaker than the signals of our devices.

Table 4 shows the locations of the server, the APs, and the hosts in the fields. Both the high and low interference cases are examined. For the high level case, all the devices for the three links are located in the same room. For the low level case, the devices for each link are located in each of three different rooms.

5.3 Channel Assignments to APs

Channel 1 for non-CB is always assigned to AP1. Either of channel 1, 6, or 13 is assigned to AP2. To AP3, the assigned channel is moved from channel 1 to channel 13 one by one, so that chD is gradually increased. The throughputs for all the links are measured at the same time.

5.4 Throughput Results

Figures 6 and 7 illustrate the throughput measurement and estimation results for the high and low interferences, respectively. In each Figure, the left graph reveals the results in Engineering Building #2 and the right graph does the ones at the Graduate School Building. In each case, the measurement results and the estimation ones appear to be similar, which confirms the accuracy of the proposed model.

5.5 Discussions

Here, we discuss the details of throughput results for different channel assignments.

5.5.1 Different Channel Assignments

First, we discuss the results for different channel assignments.

![Fig. 4](Network topology.)

Table 4 Device locations.

| interference level | field       | device location | AP1, HOST1 | AP2, HOST2 | AP3, HOST3 |
|--------------------|-------------|----------------|------------|------------|------------|
| high               | Eng. Bldg. #2 | D306           | D306       | D306       |
|                    | Grad. Sch. Bldg. | H            | H          | H          |
| low                | Eng. Bldg. #2 | D307            | D307       | D307       |
|                    | Grad. Sch. Bldg. | A            | E          | C          |
(1) Case (a) $AP_1$: $ch_1$, $AP_2$: $ch_1$

The throughput is low when $AP_3$ is assigned channel 1 – 4. Here, the three APs are assigned to the same or quite close channels, which causes the high interference. Then, the throughput will turn out to be high when $AP_3$ is assigned channel 8 – 13, where the interference becomes low.

(2) Case (b) $AP_1$: $ch_1$, $AP_2$: $ch_6$

The throughput is medium when $AP_3$ is assigned channel 1 – 6. The three APs are assigned to the similar channels, which causes the medium interference. Then, the throughput becomes highest when $AP_3$ is assigned channel 13, where the three APs are assigned almost non-interfered channels. Thus, the interference becomes exceedingly low.

(3) Case (c) $AP_1$: $ch_1$, $AP_2$: $ch_{13}$

The throughput is highest when $AP_3$ is assigned channel 7, where the three APs are assigned the non-interfered channels. Then, when the channel of $AP_3$ is close to channel 1 or channel 13, the throughput is reduced on account of the higher interference.

(4) Estimation Curve

The curve of the estimated throughput is not smooth but has convex or concave, because the throughput drop by the interference is changed non-linearly depending on the channel distance between the assigned channels and on (RSSi) of the interfering signal at the AP. When the channel distance is small or (RSSi) is large, the interference is large and the estimated throughput becomes smaller. On the other hand, when the channel distance is large or (RSSi) is small, the interference is small and the estimated throughput becomes larger.

5.5.2 Different Interference Levels

Next, we analyse the results for different interference levels. The throughput for the high interference level is generally lower than the throughput for the lower one. When the non-interfered channels are assigned to the three APs, the throughput for the high level is similar to the throughput for the lower one. Thus, the non-interfered channels should be assigned to the APs when they are highly interfered.

5.5.3 Improvement of Model

Overall, the experiment results confirm the accuracy of the proposed model under various interference conditions among three links. However, the gap between the measured and estimated throughputs is relatively large when $AP_3$ is assigned channel 1 – 4 for the high interference level. In this situation, the collision avoidance mechanism of the CSMA/CA protocol [40] may work properly to avoid the further throughput drop. The improvement of the model under high interfering situations will be involved in our future works.
5.6 Evaluation for Different AP Device

To verify the generality of the proposed model, we evaluate the accuracy using different AP devices.

5.6.1 Measurement Scenario

Here, we adopt the *Raspberry Pi 3 Model B* for the APs, which uses Raspberry OS, Broadcom BCM2837, 1.2Ghz 64-bit quad-core ARM Cortex-A53 CPU, LPDDR2-900MHz 1GB SDRAM, 10/100Mbps Ethernet, IEEE802.11b/g/n wireless NIC, Blue-tooth 4.1 classics/low energy [41].

| channel distance | p   | q   | r   |
|------------------|-----|-----|-----|
| 0                | 6.0 | 90.0| 1.5 |
| 1                | 6.0 | 85.0| 1.0 |
| 2                | 5.5 | 84.5| 1.0 |
| 3                | 5.0 | 79.5| 0.5 |
| 4                | 5.0 | 62.0| 0.5 |
| 5                | 3.2 | 60.0| -0.25 |

5.6.2 Results and Discussions

Figure 8 shows the average throughput of the two links when the channel distance $chD$ between them is changed from 0 to 12. Again, the average throughput is small due to the strong interference when the channel distance is smaller than 5.

Figure 9 shows the changes of the measured and estimated throughput drop of the first link using the Raspberry Pi AP when the three parameter values in Table 5 are used and the channel distance $chD$ is changed. Again, the logarithm function in the model is well matching with the measured throughput.

Figure 10 shows the average measured and estimated throughput of the three links with the Raspberry Pi AP. Again, the estimated throughput is well matching with the measured throughput. Therefore, the proposed model can be used for various AP devices.

6. Evaluation of Channel Assignment by Proposed Model

In this section, we present the application of the throughput drop estimation model to the channel assignment to the APs in WLAN.
6.1 Modifications of Algorithm

The channel assignment phase of the active AP configuration algorithm in [42] is modified to assign the non-CB POC using the proposed model. The modifications of the problem formulation for this phase are described as follows.

6.1.1 Input and Output

In the output, non-CB POCs are assigned to the active APs, instead of non-CB orthogonal channels (OCs). Then, in the input, the number of channels \( C \) represents the number of non-CB POCs.

6.1.2 Objective

In the objective, the new cost function \( E_{ch} \) in Eq. (10) is designed to maximize the total throughput of the APs, while it minimizes the difference of the communication time between the fastest AP and the slowest one. The latter part of the function intends averaging the performances of the APs.

\[
E_{ch} = \sum_{i=1}^{N} T P_{i}^{POC} - \alpha (\text{max}_i[C T_{i}^{POC}] - \text{min}_i[C T_{i}^{POC}])
\]

where \( T P_{i}^{POC} \) represents the total throughput of the links associated with \( A P_i \) under the POC assignment, \( C T_{i}^{POC} \) does the required time for every link associated with \( A P_i \) to transmit one bit, and \( \alpha \) does the coefficient in the function. The function \( \text{max}_i[x_i] \) (\( \text{min}_i[x_i] \)) returns the maximum (minimum) value of \( x_i \). \( C T_{i}^{POC} \) is particularly small compared to \( T P_{i}^{POC} \). Thus, a large value of \( \alpha = 10000 \) is used in this paper.

The communication time \( C T_{i}^{POC} \) is defined by the total time required for the \( A P_i \) to transmits 1-bit data to all of the hosts associated with the AP. When the communication time for \( A P_i \) is small, the throughput is large, since it is given by the inverse of the communication time. Therefore, the communication time should be minimized to maximize the throughput.

\[
T P_{i}^{POC} = \frac{1}{\sum_{j \in A H_i} t p_{ij}^{POC}}
\]

6.2 Evaluations by Simulations

First, we evaluate the POC assignment using the proposed model through simulations on regular and random topologies. The WIMNET simulator [43] is adopted in our simulations. Table 6 summarizes the parameters for them.

| parameter       | value                  |
|-----------------|------------------------|
| packet size     | 1,500 bytes            |
| max. transmission rate | 75 Mbit/s              |
| propagation model | log distance path loss model |
| rate adaptation model | sigmoid function     |
| carrier sense threshold | −85 dBm               |
| transmission power | 19 dBm                 |
| collision threshold | 10                    |
| RTS/CTS         | yes                    |

Table 7 Simulation results for Engineering Building #2.

| channel assignment | OC | # of channels | small. through. (Mbps) | total through. (Mbps) |
|-------------------|----|---------------|------------------------|----------------------|
|                   | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|                   | 6.134 | 6.053 | 6.836 | 6.977 | 7.696 | 7.698 | 7.836 | 7.831 | 7.918 | 7.918 |
|                   | 190.151 | 206.252 | 211.922 | 216.289 | 238.587 | 242.911 | 242.773 | 242.935 | 245.463 | 245.463 |

Table 8 Simulation results for Graduate School Building.

| channel assignment | OC | # of channels | small. through. (Mbps) | total through. (Mbps) |
|-------------------|----|---------------|------------------------|----------------------|
|                   | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|                   | 6.289 | 7.241 | 7.243 | 7.694 | 7.887 | 8.008 | 8.235 | 8.237 | 8.334 | 8.477 | 8.477 |
|                   | 301.867 | 347.547 | 347.653 | 369.324 | 378.569 | 384.490 | 395.300 | 395.386 | 400.022 | 406.890 | 406.890 |
6.2.1 Regular Topology

Figure 11 shows the network fields and the AP and host locations in simulations. Figure 11 (a) models the third floor in Engineering Building #2. 9 APs and 31 hosts are located in the nine rooms, where each room size is either $7m \times 6m$ or $3.5m \times 6m$. Figure 11 (b) models the second floor in Graduate School of Natural Science and Technology Building. 13 APs and 48 hosts are located in the eight rooms and the corridor.

Tables 7 and 8 present the smallest throughput of one host among the hosts and the total throughput of all the hosts for the two fields respectively, when the number of POCs is changed from three to 13. In both topologies, when the number of POCs is 12 or 13, both throughputs become highest, where the proper POC assignment using the model reduces the interference.

The POC assignment improves the smallest throughput by 24.766% and the total throughput by 24.771% on average in the two topologies from the OC assignment. Thus, the POC assignment using the proposed model outperforms the conventional OC assignment.

6.2.2 Random Topology

The channel assignment using the proposed model is simulated in a random topology of size $40m \times 30m$ in Fig. 12. 10 APs and 30 hosts are located in the field. Table 9 shows the results where the proposal improves the smallest throughput of one host by 19.624% and the total throughput of all the hosts by 19.620% on average from the OC assignment. The effectiveness of POC assignment by the proposed model is verified in a different network topology.

6.3 Evaluations by Experiments

Next, we evaluate the POC assignment using the proposed model through testbed experiments in two topologies in Engineering Building #2. Figure 13 illustrates the locations of the four APs and the four hosts in topology 1. In topology 2, the AP and the host in room D4 are moved to D307 for higher interferences. In each topology, three channels (1, 7, 13) are used for the OC assignment, while four channels (1, 5, 9, 13) are for the POC assignment.

Figures 14 and 15 show the total throughput results for topology 1 and topology 2 respectively. In either topology, the channel assignment with four POCs by the proposal improves the measured one by 12.89% on average over the assignment with three OCs. Besides, the measured throughput and the simulated one are similar to each other. Again, the effectiveness of the proposed POC assignment and the accuracy of the proposed throughput drop estimation model are both confirmed.

7. Conclusion

This paper studied the throughput drop estimation model for concurrently communicating multiple links without

![Fig. 12](image-url)
using the channel bonding (CB) in the wireless local-area network (WLAN), and its application to the partially overlapping channel (POC) assignment to the access-points (APs). The accuracy of the model was confirmed through experiments in two network fields where the small average error of 9.946% and 6.285% for high and low interference cases was observed. The effectiveness of the POC assignment using the model was verified through simulations and experiments in various topologies, where the proposal improves the total throughput by 22.196% in simulations and by 12.89% in measurements on average. In future works, we will improve the model to consider both the CB and non-CB links together, and evaluate it in various topologies.

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