Throughput Measurement and Estimation Model for Concurrent Communications of Multiple Raspberry Pi Access-Points in Wireless Local-Area Network

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Abstract —Recently, *Raspberry Pi* has become popular around the world as an inexpensive, small, and powerful computing device. We have studied its use as the *software access-point (AP)* for the *IEEE 802.11n wireless local-area network (WLAN)*, where the *channel bonding (CB)* can increase the throughput by bonding two channels into one. However, the built-in *wireless network interface card (NIC)* adapter fails to support the CB. Thus, we have configured the CB using external NIC adapters, and investigated the throughput performance and estimation model for only one link between a PC host and a Raspberry Pi AP. In this paper, we present the throughput measurement for *concurrent communications* of multiple links with up to three APs under different adapters and channels with 11 and 13 *partially overlapping channels (POCs)* at 2.4GHz. Besides, we extend the throughput estimation model by introducing the *throughput drop factor* to consider interferences between the links. This factor can be derived from the CB use and the assigned channels for the links. The effectiveness of the proposal is verified by comparing the estimated throughput with the measured one.

Index Terms—IEEE 802.11n, access point, Raspberry Pi, channel bonding, concurrent communication, throughput estimation model

I. Introduction

As rapid developments of wireless communication and device technologies, the *IEEE 802.11 wireless local area network (WLAN)* has become prevalent in plenty of locations including universities, shopping malls, airports, and office buildings [1]. WLAN offers the inexpensive and flexible access medium to the Internet for user hosts such as PCs and smart phones, through associations with *access points (APs)* by the wireless medium. Among several protocols, *IEEE 802.11n* outweighs the others with its higher data transmission speed.

The *channel bonding (CB)* is the key technology in IEEE 802.11n [2]. The CB can increase the number of sub-carriers in *Orthogonal Frequency-Division Multiplexing (OFDM)* from 52 to 108 by bonding two 20MHz channels [3], reduce the *guard interval time*, and enhance the *frame aggregation*.

Recently, *Raspberry Pi* has been widespread as a cost-effective, energy-saving, portable, and powerful computing device [4]. We have studied the use of Raspberry Pi for the IEEE 802.11n *software AP* by running *hostapd* software with its built-in *wireless network interface card (NIC)* adapter [5]-[7]. However, this AP only offers the link to the *non-channel bonding (non-CB)* channel, because the built-in NIC adapter in Raspberry Pi does not support the CB functionality due to its adopted device. Therefore, we explored the CB configuration for the Raspberry Pi AP using an external NIC adapter, and investigated the throughput performance and the throughput estimation model for the single link communication. The measurement results show the superiority of the CB over the non-CB [8].

Practically, the *concurrent communications* of multiple links within the interference range often appear in WLAN. In IEEE 802.11n, the limited number of channels is available, and the spectrums of adjacent channels are overlapped with each other, called *partially overlapping channels (POCs)* [9]. Actually, *11 POCs* are available at 2.4GHz in many countries, whereas *13 POCs* can be used in Japan and Europe. Arunesh et al. suggest that if many APs are deployed in the network field, the proper assignment of POCs to APs will be critical to maximize the throughput performance [10]. As the result of the strong interference, the throughput performance of the concurrent communications appears to be much different from that of the single link one.

To design the efficient WLAN system, the accurate *throughput estimation model* is essential to evaluate the performance of the current configuration of the system by simulations. Thus, we have studied the throughput estimation model, which first estimates the *received signal strength (RSS)* at the host using the *log distance path loss model* and then, converts the RSS to the throughput using the *sigmoid function* [11]. However, this model only considers the single link communication, and needs to be extended for the concurrent communication.

In this paper, we first present the throughput measurement results in the concurrent communications of

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up to three Raspberry Pi APs and PC hosts for 11 POCs. To examine various conditions, we adopt different wireless NIC adapters and change the *channel distance (ChD)* among the APs. Then, we modify the existing throughput estimation model based on the measurement results. The *reduction factor* is introduced to consider the *throughput drop* due to the interference among the concurrently communicating links, which is derived from the use/non-use of the CB and the *ChD* at the links. These are the generalizations of our preliminary works in [12]. Finally, we extend these works to 13 POCs to confirm the effectiveness in the wider spectrum for WLAN. Two non-interfered channels for the CB are available theoretically for 13 POCs, which has a potential of greatly increasing the transmission capacity of WLAN.

For 11 POCs, the throughput measurement results show that the total throughput is mostly constant regardless of the *ChD* when two CB APs are adopted, and increases as the *ChD* when that one CB AP and one non-CB AP is used. Besides, the total throughput for the latter case is larger than the former case when the *ChD* between the two APs is large enough. The comparisons between the throughput measurement results and the estimated ones by the model confirm the effectiveness of the extended model.

For 13 POCs, the throughput measurement results show that the total throughput is much higher when two CB APs are used with the non-interfered channels for the two APs case, and it is highest when two non-CB APs and one CB AP are used with the non-interfered channels for the three APs case. The modified throughput estimation model also well estimates the measured throughputs for them.

The rest of this paper is organized as follows: Section II reviews the related works. Sections III presents the throughput measurement for concurrent communications. Section IV modifies the throughput estimation model. Section V shows the evaluation results. Section VI shows the extension of this work to 13 POCs. Finally, Section VII concludes this paper with future works.

II. Preliminary Works

In this section, the related preliminary works will be reviewed.

A. Throughput Estimation Model

This model estimates the throughput or the data transmission capacity of an IEEE 802.11 link. First, it estimates the RSS at the host using the *log distance path loss model* [13]. Then, it estimates the throughput from that RSS using the *sigmoid function*. Both functions have several parameters that can affect the estimation accuracy, where their proper values depend on link specifications and network field environments.

1) Log distance path loss model: The RSS, *Pd (dBm)*, at the host is estimated using the *log distance path loss model*:

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

where P_1 represents the signal strength at *1m* from the AP (source), ω does the path loss exponent, *d (m)* does the distance from the AP, n_k does the number of the type-*k* walls along the path between the AP and the host, and W_k does the signal attenuation factor *(dBm)* for the type-*k* wall in the environment. The estimated accuracy of RSS relies on the parameter values, which depend on the propagation environment.

2) Multipath Effect: Due to the multipath effect in indoor environments, the receiver may receive the indirect signal that arrives after diffracted at random points on a wall or an obstacle, in addition of the direct signal along the *line of sight (LOS)*. When the direct signal passes through multiple walls, the RSS becomes weaker than that of the indirect signal if it passes through fewer walls.

In the throughput estimation model, we consider this multipath effect by selecting a *diffraction point* for each AP/host link such that it is located on a wall in the same room as the host and RSS from the AP is largest. The RSS through the indirect path P_{ind} is calculated by:

$$P_{dif} = P_1 - 10.\omega.log_{10}r - \sum_k n_k W_k \tag{2}$$

$$P_{ind} = P_{dif} - 10.\omega.log_{10}t - W_{dif} \tag{3}$$

where P_{dif} represents the RSS at the diffraction point, *r (m)* does the distance between the AP and the diffraction point, *t (m)* does the distance between the diffraction point and the host, and W_{dif} *(dBm)* does the attenuation factor at the diffraction point. For the estimated RSS at the receiver, the larger one of the direct or indirect signals is selected.

3) Sigmoid Function: From the RSS, the throughput *S (Mbps)* of the link is derived using the sigmoid function:

$$S = \frac{a}{1+e^{-\left(\frac{(P_d+120)-b}{c}\right)}} \tag{4}$$

where *a*, *b*, and *c* are the constant parameters that should be optimized.

4) Parameter Optimization Tool: The parameter optimization tool is used to explore the optimal parameter values for the throughput estimation model [14]. It uses the *tabu table* and the *hill-climbing procedure* to avoid a local minimum. This tool searches the parameter values that minimize the throughput estimation error.

B. Partially Overlapping Channel and Channel Bonding

In the CB, *channel 1* on 20MHz is bonded to *channel 5* to configure *channel 1+5* on 40MHz, as shown in Fig. 1. When 13 POCs are available, which is available in specific countries such as Japan, 9 bonded POCs can be used. When 11 POCs are available, which is common in many countries, 7 bonded POCs can be used. Both are considered in this paper.

The *channel distance (ChD)* of two links, namely $link_1$ and $link_2$, is defined as the minimum difference between the assigned channels to them. For example, when both links are assigned the same channel: *ChD = 0*, and they are fully overlapped. When $link_1$ is assigned *channel 3* and $link_2$ is *channel 5*, *ChD = 2*. In this case, these channels are overlapped by 50% for 20MHz, and by 75% for 40MHz. In this paper, the maximum *ChD* is 8.

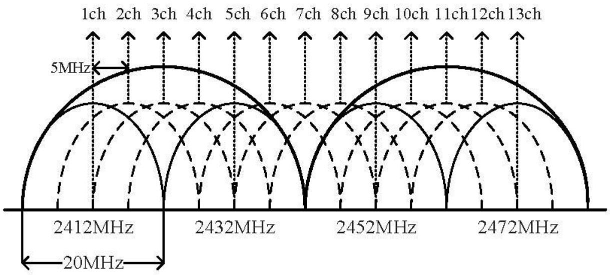


Fig. 1. Partially overlapping channels with channel bonding.

III. Throughput Measurement for Concurrent Communication

In this section, we present the throughput measurement results in the concurrent communication of multiple Raspberry Pi APs for 11 POCs.

A. Measurement Setups

Table I shows the adopted devices and software specifications in the measurement.

TABLE I: DEVICES AND SOFTWARE SPECIFICATIONS FOR MEASUREMENTS

AP	model	Raspberry Pi 3
	CPU	Broadcom BCM2837 @1.2Ghz
	memory	1Gb LPDDR2 900Mhz
	OS	Raspbian
	AP	hostapd
	external NIC	IO-Data WN-AC433UA/ TP-LINKTL-WN722N
PC server	model	Fujitsu Lifebook S761/C
	CPU	Intel Core i5-2520M @2.5Ghz
	memory	4GB DDR3 1333Mhz
	OS	Windows 7
	TCP	iperf 2.0.5
PC host	model	Toshiba Dynabook R731/B
	CPU	Intel Core i5-2520M @2.5Ghz
	memory	4GB DDR3 1333Mhz
	OS	Windows 7/10
	TCP	iperf 2.0.5

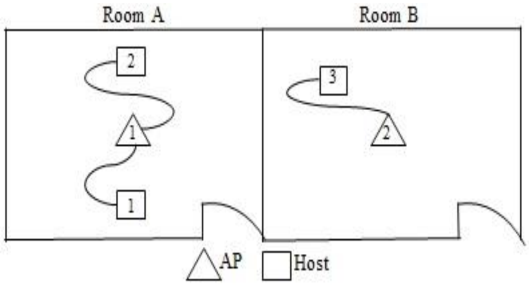
Table II reveals the specifications of the adopted wireless NIC adapters in the measurement. To illustrate, one combination of Raspberry Pi and the NIC adapter is called the AP type. AP types 1 and 2 use the external NIC for the CB, and AP type 3 uses the built-in NIC for the non-CB.

TABLE II: WIRELESS NIC ADAPTERS.

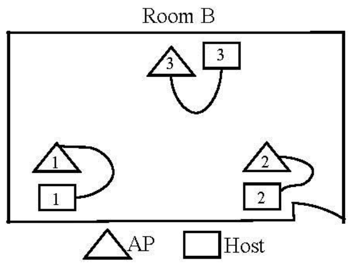
AP Type	NIC CB	model	wireless chipset	fre-quency	channel width
1	USB, CB	IO-Data WN-AC433UA	Realtek RTL8811AU	2.4GHz	20MHz, 40MHz
2	USB, CB	TP-LINK TL-WN722N	Atheros AR9002U	2.4GHz	20MHz, 40MHz
3	built-in, non-CB	Raspberry Pi 3	Broadcom BCM43438	2.4GHz	20MHz

B. Network Topologies

Fig. 2 demonstrates the network topologies for measurements on the 3rd floor of Engineering Building #2 in Okayama University. The triangle represents the AP and the rectangle does the host. The rooms A and B have the same size of 7m × 6m. In any case, all the hosts are concurrently communicating with the associated APs simultaneously.



(a) network topology for two APs case.

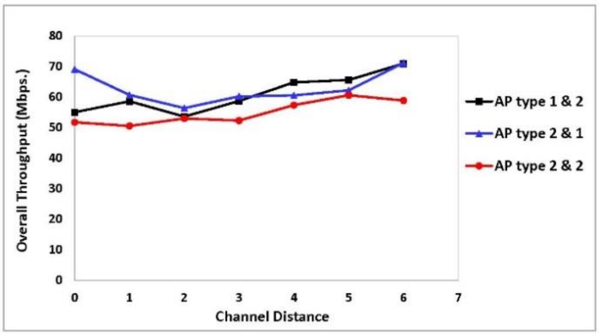


(b) network topology for three APs case.

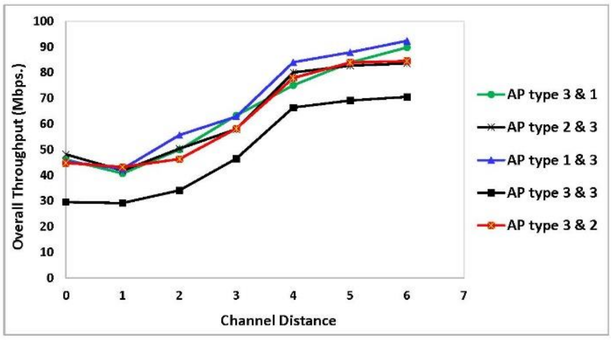
Fig. 2. Network topology.

C. Results for Two APs Case

Fig. 3 (a), (b) show the total throughput results in the two APs case for the use of only CB APs, and for the use of a CB and a non-CB AP respectively. In Fig. 3 (a), the total throughput is mostly constant regardless of the *ChD* due to the large interference among the two APs. In Fig. 3 (b), it is improved as the *ChD* increases, since the interference becomes smaller. The total throughput is highest in the latter case at AP type = 1 & 3 and *ChD* = 6.



(a) results of CB AP only.



(b) results of CB AP + non-CB AP.

Fig. 3. Throughput measurement results of two APs case.

Table III exhibits the individual throughput of each AP for the four combinations of AP types. For example, the two APs in the first combination offer different throughput results for the most *ChD*, although they have the same AP type. In WLAN, this can often happen because of the unfairness of transmission opportunities between interfered links. Therefore, in this paper, we use the *total throughput* of the APs in the network for evaluations.

TABLE III: MEASUREMENT RESULTS FOR TWO APS CASE.

AP type	channel distance (*ChD*) 0	1	2	3	4	5	6
2	25.70	15.40	31.74	41.34	19.2	19.99	32.14
2	26.07	35.16	21.3	11	38.2	40.65	26.77
2	13.84	7.75	13.03	8.2	10.8	25.4	50.76
1	55.26	52.95	43.38	52.05	49.75	36.85	20.47
2	35.3	27.21	36.65	42.55	42.18	47.25	48.46
3	12.9	14.65	13.75	15.5	37.95	35.5	35.15
3	26.61	25.29	24.11	26.88	34.72	33.09	33.97
2	18.24	18	22.27	31.36	43.26	50.89	50.58

D. Results for Three APs Case

Table IV shows the total throughput results in the three APs case. It indicates that no. 6 provides the best total throughput, where two non-CB APs are assigned *channels 1* and *11*, and one CB AP is *channel 1+5*. In this combination, the non-CB AP with *channel 11* and the CB AP with *channel 1+5* are not interfered.

As well, no. 9 provides the similar total throughput, where three non-CB APs are assigned *channels 1*, *6*, and *11* as the non-interfered channels. Depending on the host distribution in the network field, either of no. 6 or no. 9 should be adopted. When an area in the field is congested with many hosts, no. 6 should be adopted, because the CB AP can offer higher throughput for the congested hosts than the non-CB AP. When hosts are distributed evenly, no. 9 should be adopted. Table IV shows that no. 7 does the worst throughput, where three non-CB APs are assigned the same channel.

TABLE IV: THROUGHPUT MEASUREMENT RESULTS FOR THREE APS CASE

no.	CB (AP1, AP2, AP3)	Channel (AP1, AP2, AP3)	throughput (Mbps) AP 1	AP 2	AP 3	total
1	all CB	1+5, 1+5, 1+5	10.58	12.35	34.85	57.78
2	all CB	1+5, 7+11, 1+5	10.49	13.5	31.63	55.62
3	non-CB, CB, CB	11, 4+8, 1+5	28.9	2.95	59.1	90.95
4	non-CB, CB, CB	11, 7+11, 1+5	38.49	12.21	46.14	96.84
5	non-CB, non-CB, CB	8, 11, 1+5	5.6	26.9	51.2	83.7
6	non-CB, non-CB, CB	1, 11, 1+5	23.62	33.87	41.4	98.90
7	all non-CB	11, 11, 11	12.2	8.94	9.43	30.58
8	all non-CB	1, 11, 11	37.15	11.13	27.78	76.06
9	all non-CB	1, 6, 11	32.6	32.9	31.5	97.00

IV. MODIFICATION OF THROUGHPUT ESTIMATION MODEL

In this section, we present the modifications of the throughput estimation model for the concurrent communication of multiple APs based on the results in Section III.

A. Modification for Two APs Case

First, we examine the two APs case.

1) CB AP Only: When only the CB APs are used, the total throughput is mostly constant at any *ChD* as in Figure 3 (a). Thus, the throughput (transmission speed) of any link is reduced by the following constant factor *F(ChD)*, called the *reduction factor*, from the one estimated by the original model.

$$F\ (ChD) = 0.6 \tag{5}$$

2) CB AP and Non-CB AP: When the CB AP and the non-CB AP are used, the total throughput increases as the *ChD* increases, as shown in Fig. 3 (b). Thus, the throughput of any link is reduced by the reduction factor *F(ChD)* in Eq. (6), from the one estimated by the original model.

$$F(ChD) = \begin{cases} 0.46 & if\ ChD \le 2 \\ 0.115 \times ChD + 0.26 & otherwise \end{cases} \tag{6}$$

B. Modification for Three APs Case

Next, we examine the three APs case. From the results in Table IV, the throughput features in the three APs case can be classified into the following four cases:

1) All the APs are CB.
2) All the APs are non-CB and assigned the same channel.
3) All the APs are non-CB and assigned the non-interfered three channels, namely *1*, *6* and *11*.
4) At least one AP is non-CB and assigned the non-interfered two channels.

In the first and second cases, all the APs are interfering with each other. Thus, the total throughput can be reduced by a large constant factor.

In the third case, all the APs do not interfere with each other, and the total throughput can be reduced by a small constant factor.

In the fourth case, the total throughput of the two APs that have not interfered with each other, can be reduced by a small constant factor, and the throughput of the last AP that is interfered by either of the other two APs, can be reduced by a large constant factor. It is noted that one non-CB AP and one CB/non-CB AP are not interfering with each other, if they are assigned *channels 1* and *7+11/11*.

Then, by examining several values for the constant reduction factors, the following equation is introduced to approximate the total throughput *TS (Mbps)* using the throughput estimation model:

$$TS = \begin{cases} (x+y+z)\times\beta^2 & for\ case\ 1) \\ (x+y+z)\times\gamma^2 & for\ case\ 2) \\ (x+y+z)\times\alpha^2 & for\ case\ 3) \\ (x+y)\times\alpha^3 + z\times\gamma & for\ case\ 4) \end{cases} \tag{7}$$

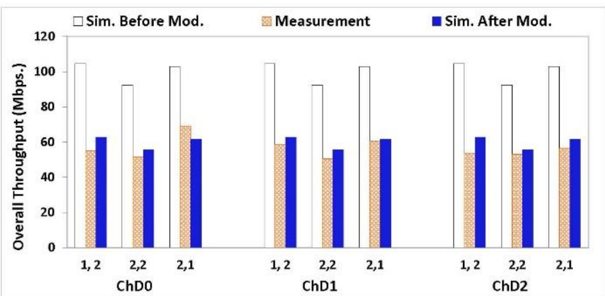
where x, y, and z represents the estimated throughput of each AP using the original throughput estimation model for the single communication. Specifically, x and y does the throughput for the two APs that have not interfered with each other, and z does the throughput for the remaining AP. α, β, and γ represents the constant reduction factors, where $\alpha = 0.95$, $\beta = 0.6$, and $\gamma = 0.46$ are used in this paper. $\beta = 0.6$ comes from Eq. (5) for CB AP only in the two APs case. $\alpha = 0.95$ and $\gamma = 0.46$ come from Eq. (6) for CB AP + non-CB AP in the two APs case with $ChD = 6$ ($0.115 \times 6 + 0.26 = 0.95$) and with $ChD = 0$, respectively.

V. Evaluation

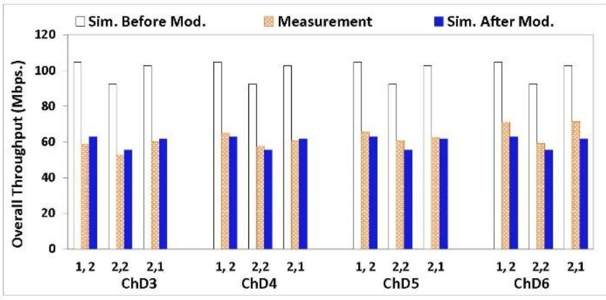
In this section, we evaluate the modified throughput estimation model through comparing the estimated throughput results with the measured ones for 11 POCs. To estimate the throughput under the concurrent communication of multiple links by the original model, we adopt the *WIMNET simulator* to consider the interference.

A. Results for Two APs Case

Fig. 4 and Fig. 5 compare the three throughput results from the original model, the measurement, and the modified model in the two APs case with CB AP only and with CB AP + non-CB AP, respectively. Table V summarizes the average and the standard deviation (SD) of the throughput estimation errors of the original model and the modified model for them. It has been proved that the modified model greatly improves the estimation accuracy in the two APs case.

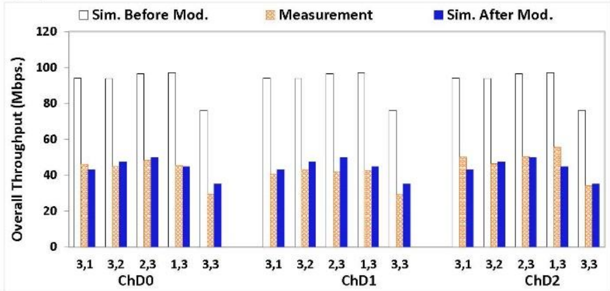


(a) results of *ChD* = 0, 1, 2.

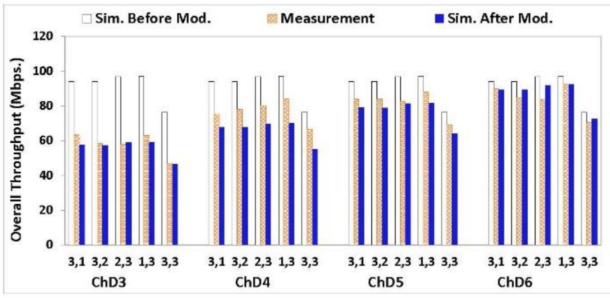


(b) results of *ChD* = 3, 4, 5, 6.

Fig. 4. Throughput comparisons in two APs case with CB AP only.



(a) results of *ChD* = 0, 1, 2.



(b) results of *ChD*=3, 4, 5, 6.

Fig. 5. Throughput comparisons in two APs case with CB AP + non-CB AP.

B. Results for Three APs Case

Fig. 6 compares the three throughput results in the three APs case. In any result, the modified model can estimate the measured throughput accurately, which confirms the effectiveness of our proposal. Table V also shows the average and the standard deviation (SD) of the throughput estimation errors in this case, which indicates that the modified model greatly reduces the estimation error in the three APs case.

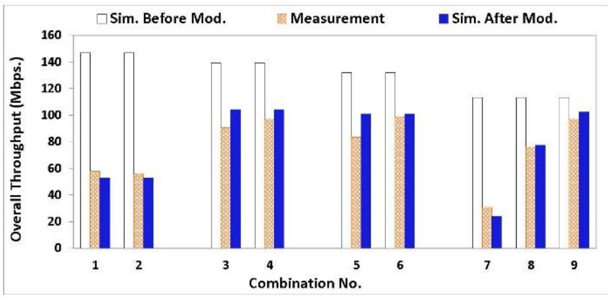


Fig. 6. Throughput comparisons of three APs case.

TABLE V: SUMMARY OF THROUGHPUT ESTIMATION ERRORS.

case		original model average (Mbps)	original model SD (Mbps)	modified model average (Mbps)	modified model SD (Mbps)
2APs CB only	1, 2	43.57	6.28	5.46	2.85
	2, 2	37.52	3.96	3.53	1.19
	2, 1	39.91	5.29	3.76	3.65
2APs CB+non-CB	3, 1	29.88	19.32	4.41	2.52
	3, 2	21.29	18.53	8.88	4.85
	2, 3	21.39	18.05	8.95	5.68
	1, 3	29.79	20.74	5.49	5.35
	3, 3	26.82	19.03	4.41	3.94
3APs		54.32	26.84	6.81	5.34

VI. EXTENSION TO 13 PARTIALLY OVERLAPPING CHANNELS

In this section, we extend the throughput measurement and the throughput estimation model to 13 POCs.

In some countries including Japan, 13 POCs can be used at 2.4GHz. As shown in Fig. 1, two non-interfered bonded POCs are available for CB APs in this case. Unfortunately, the *IO-Data WN-AC433UA* does not support 13 POCs. Thus, the *TP-link TL-WN722N* external NIC and the built-in NIC are adopted in the experiments.

A. Two APs Case

First, we discuss the results in the two APs case.

1) CB AP Only: Fig. 7 shows the total throughput measurement results in the two APs case with 13 POCs. When only the CB APs are used, the total throughput is almost constant up to *ChD = 6*. For *ChD = 7* and *8*, the throughput increases because the interference between the two APs is decreased. Especially, for *ChD = 8*, the throughput is greatly improved because of the non-interference theoretically.

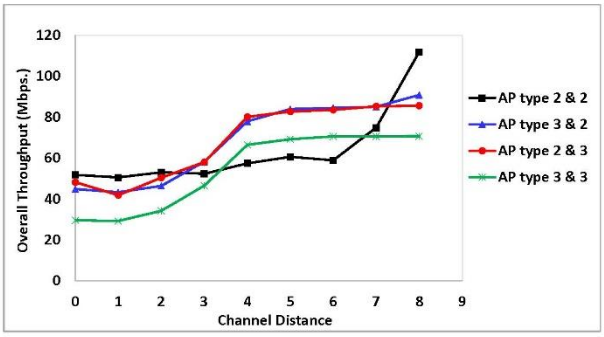


Fig. 7. Throughput measurement results in two APs case with 13 POCs.

Then, the reduction factor *F(ChD)* to estimate the transmission speed for the two CB APs is modified as follows:

$$F(ChD) = \begin{cases} 0.6 & if\ ChD \leq 6 \\ 0.19 \times ChD - 0.5533 & if\ ChD > 6 \end{cases} \quad (8)$$

2) CB AP and Non-CB AP: When the CB AP and the non-CB AP are used, the total throughput increases as *ChD* increases. However, this increase rate becomes small after *ChD = 7*. Thus, the reduction factor is modified as follows:

$$F(ChD) = \begin{cases} 0.46 & if\ ChD \leq 2 \\ 0.115 \times ChD + 0.26 & if\ 3 \leq ChD \leq 6 \\ 0.005 \times ChD + 0.92 & if\ ChD \geq 7 \end{cases} \quad (9)$$

3) Model Evaluation Results: Fig. 8 compares the total throughput results by the original model, the measurement, and the proposed model, for the CB AP only, and for the CB AP and the non-CB AP, in the two APs case with 13 POCs, respectively. It indicates that our modified throughput estimation model can estimate the throughput with the high accuracy.

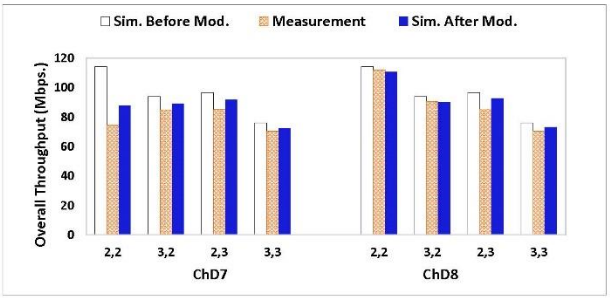


Fig. 8. Throughput comparisons at *ChD* = 7 and 8 for two APs case with 13 POCs.

B. Three APs Case

Next, we discuss the results in the three APs case.

1) Measurement Results: Table VI shows the total throughput results in the three APs case. It indicates that no. 2 provides the best total throughput, where two non-CB APs are assigned *channel 1* and *5*, and one CB AP is *channel 9+13*. In this combination, all the APs use the non-interfered channels.

TABLE VI: THROUGHPUT MEASUREMENT RESULTS IN THREE APS CASE WITH 13 POCS.

no.	CB (AP1, AP2, AP3)	Channel (AP1, AP2, AP3)	throughput (Mbps) AP 1	AP 2	AP 3	total
1	all non-CB	1, 9, 13	34.4	37.7	36.7	108.8
2	non-CB, non-CB, CB	5, 1, 9+13	26.6	31	61.2	118.8
3	non-CB, CB, CB	13, 9+13, 1+5	24.25	14.39	67.65	106.29

2) Modification of Throughput Estimation Model: Then, we examine the medication of the throughput estimation model for the three APs case. From the results in Table VI, the throughput features can be classified into the following three cases:

1) All the APs are non-CB, and are assigned the non-interfered three channels.
2) One AP is CB and two APs are non-CB, and are assigned the non-interfered three channels.
3) At least one AP is non-CB, and the APs are assigned the non-interfered two channels.

Then, the following equation is introduced to approximate the total throughput *TS (Mbps)* using the throughput estimation model:

$$TS = \begin{cases} (x + y + z) \times \alpha^2 & for\ case\ 1)\ and\ 2) \\ (x + y) \times \alpha^3 + z \times \gamma & for\ case\ 3) \end{cases} \quad (10)$$

where x, y, and z represents the estimated throughput of each AP using the throughput estimation model for the single communication. Specifically, for case 3), x and y does the throughput for the two APs that are not interfered with each other, and z does the throughput for the remaining AP. α and γ represent the constant reduction factors, where $\alpha = 0.96$, and $\gamma = 0.46$ are used in the paper.

3) Model Evaluation Results: Fig. 9 compares the total throughput results by the original model, the measurement, and the modified model for the CB AP only, and for the CB AP and the non-CB AP, in the three APs case with 13 POCs, respectively. Again, it indicates that our modified throughput estimation model can estimate the throughput with the high accuracy.

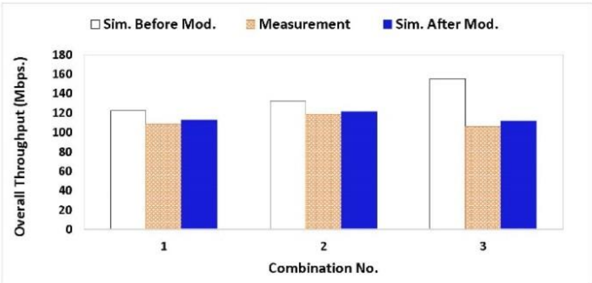


Fig. 9. Throughput comparisons of three APs case with 13 POCs.

VII. Conclusions

This paper presented throughput measurements and modifications of the throughput estimation model for the concurrent communication of multiple IEEE 802.11n links using up to three Raspberry Pi soft APs. The effectiveness of the proposal was confirmed by comparing estimated throughput with measured ones. Our future works will involve further extensions of the model to the concurrent communication with four or more APs in the network field, evaluations in various network fields, and applications of the model to optimal WLAN designs.

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