A Study of Transmission Power Optimization Considering Channel Assignment for Access-Points in Wireless Local-Area Network

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TO WHOM IT MAY CONCERN

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Abstract

Currently, *IEEE 802.11n wireless local-area network (WLAN)* has been prevalent among the societies around the world due to its flexibility, scalability, and affordability. WLAN offers the wireless Internet-access method through *access points (APs)* for hosts in many places such as homes, schools, or offices. WLAN can easily expand the coverage area by allocating new APs in the network field.

In WLAN, when multiple APs are densely deployed in a network field, interferences among them may cause the reduction of the network performance. Therefore, we have studied the *elastic WLAN system* that dynamically optimizes the network configuration depending on the network conditions, in order to reduce the interferences and enhance the performance. We have developed the *elastic WLAN system testbed* using *Raspberry Pi* for APs by running *hostapd* to evaluate the performance.

To improve the communication performance of a dense WLAN, the transmission powers of the APs should be optimized, considering the capacity, the interference, and the coverage area. The high transmission power of the AP may increase the capacity and coverage area, but increases the interference to other wireless devices. On the other hand, the low power can reduce the interference while limiting the capacity and area. Actually, our experiments with different transmission powers indicated that either the maximum or minimum power always gives the best performance. The selection should be optimized for each AP with the consideration of the channel assignment, which is the goal of the study in this thesis.

In this thesis, first, I propose the *transmission power optimization method* for two concurrently communicating APs in WLAN to improve the throughput performance. It selects either the maximum or minimum power for each AP such that *signal-to-noise ratio (SNR)* is the highest. SNR is the common metric to measure the quality of wireless communication. It can describe the link capacity and the interference at the same time by comparing the received signal and the noise. Here, *channel bonding (CB)* at 2.4GHz is adopted in order to enhance the link capacity with the large channel bandwidth. The most distant channels, *channel 1 + 5* and *channel 9 + 13*, are assigned to the APs. These channels are less interference to each other, and may give the best performance. For evaluations, the proposed method is implemented on the *elastic WLAN system testbed* using two *Raspberry Pi AP*, and extensive experiments are conducted in two buildings at Okayama University. The results confirm the effectiveness of the proposals.

Then, I generalize the *transmission power optimization method* with the channel assignment consideration for concurrently communicating multiple APs in WLAN. To simplify the optimization procedure, the channels of APs are optimized before the power optimization. First, the same channel is assigned to the nearby APs that are strongly interfered, so that the *carrier-sense multiple access with collision avoidance (CSMA/CA)* protocol can work well to control the transmissions among the conflicting links. Then, the most distant channels with the same interval are assigned to the other APs. After that, the transmission power is optimized by selecting the highest measured

SNR. To reduce the SNR measurement load, 1) the maximum power is assigned to every AP, 2) the initial RSS from the associated host is measured, 3) the minimum power is assigned to one AP in descending order of the initial RSS, and the SNR is measured, and 4) the power combination for the highest SNR is selected. For evaluations, the proposed method is implemented on the *elastic WLAN system testbed* using up to four *Raspberry Pi* APs, and extensive experiments are conducted in two buildings at Okayama University. The results confirm the effectiveness of the proposals.

Further enhancements of the *transmission power optimization method* with the channel assignment consideration and their evaluations in various network fields will be in future studies.

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List of Publications

Journal Papers

1. **Hendy Briantoro**, Nobuo Funabiki, Minoru Kuribayashi, Kwenga Ismael Munene, Rahardhita Widyatra Sudibyo, Md. Manowarul Islam, and Wen-Chung Kao, "Transmission power optimization of concurrently communicating two access points in wireless local area network," International Journal of Mobile Computing and Multimedia Communications (IJMCMC), Vol. 11, No. 4, pp. 1-25 (2020).

2. **Hendy Briantoro**, Nobuo Funabiki, Md. Mahbubur Rahman, Kwenga Ismael Munene, Minoru Kuribayashi, and Wen-Chung Kao, "Joint optimization method of channel assignment and transmission power for concurrently communicating multiple access-points in wireless local-area network," International Journal of Networking and Computing (IJNC), Vol. 11, No. 2, pp. 251-266 (2021).

International Conference Papers

3. **Hendy Briantoro**, Nobuo Funabiki, Kwenga Ismael Munene, Rahardhita Widyatra Sudibyo, Minoru Kuribayashi, and Wen-Chung Kao, "A proposal of transmission power optimization method for concurrently communicating two access-points in wireless local-area network," 2020 IEEE International Conference on Consumer Electronics - Taiwan (ICCE-TW 2020), pp. 1-2 (Taoyuan, Taiwan, 2020).

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Other Papers

5. **Hendy Briantoro**, Nobuo Funabiki, Md. Manowarul Islam, Rahardhita Widyatra Sudibyo, Kwenga Ismael Munene, and Minoru Kuribayashi, "An investigation of transmission power optimization for performance improvement at concurrent communications of multiple access-points in wireless local-area network,"IEICE General Conference, pp. S66-S67 (Tokyo, Japan, 2019).

6. **Hendy Briantoro**, Nobuo Funabiki, Md. Manowarul Islam, Rahardhita Widyatra Sudibyo, Kwenga Ismael Munene, and Minoru Kuribayashi, “An exploration of transmission power optimization method for concurrently communicating two access-points in wireless local-area network,” 21st IEEE Hiroshima Section Student Symposium (HISS), pp. 104-107 (Okayama, Japan, 2019).

7. **Hendy Briantoro**, Nobuo Funabiki, Kwenga Ismael Munene, Rahardhita Widyatra Sudibyo, Md. Mahbubur Rahman, and Minoru Kuribayashi, “An extension of transmission power optimization method for two concurrently communicating access-points associated with multiple hosts in wireless local-area network,” IEICE Technical Report, NS2020-29, pp. 43-48 (Online, Japan, 2020).

8. **Hendy Briantoro**, Nobuo Funabiki, Md. Mahbubur Rahman, Kwenga Ismael Munene, Sujan Chandra Roy, and Minoru Kuribayashi, “An improvement of transmission power optimization method considering channel assignment for concurrently communicating three access-points in wireless local-area network,” IEICE General Conference, pp. S13-S14 (Online, Japan, 2021).

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Chapter 1

Introduction

1.1 Background

Nowadays, the *IEEE 802.11n Wireless Local-Area Network (WLAN)* technology is widely used as the wireless networking standard around the world. WLANs have been implemented in many places including homes, campuses, schools, and offices, because of the advantages in flexibility, scalability, and affordability [1, 2]. WLAN provides the wireless Internet access method through *access points (APs)* for hosts to allow laptops, printers, and smartphones to communicate with each other. WLAN can easily extend the coverage area by allocating new APs in the network field.

The *IEEE 802.11 standard* was primarily released in 1997 [3, 4]. Since then, the improved versions of the IEEE 802.11 standards have been published with new features to enhance the performance of WLAN. Among them, *IEEE 802.11n* has most commonly deployed in numerous places, although the maximum throughput of the protocol is lower than newer protocols such as *IEEE 802.11ac* and *IEEE 802.11ax*. *IEEE 802.11n* adopts several enhanced features, such as *MIMO*, *Channel Bonding*, and *Frame Aggregation*, over previous IEEE 802.11 protocols, 11a, 11b, 11g.

In WLAN, the AP acts as the hub to connect the wireless and the wired links. Since the license-free band is used in WLAN, the coverage range of one AP is restricted into a small area. Accordingly, multiple APs are commonly applied in WLAN to cover the large area, which may affect interferences and degrade the network performance.

Hence, we have studied the *elastic WLAN system* that dynamically optimizes the network configuration based on the network situations, to decrease the interferences and improve the performance. The *elastic WLAN system* is designed to decrease the energy consumption while improving the performance by dynamically optimizing the network configuration depending on traffic demands and network conditions [5–8].

In the *elastic WLAN system*, three types of APs, specifically, a *dedicated AP (DAP)*, a *virtual AP (VAP)*, and a *mobile AP (MAP)*, are considered. A *DAP* signifies a commercial AP, a *VAP* does a host PC of a user in the network that installs the software of AP functions [9, 10], and a *MAP* does a mobile router. Figure 1.1 shows the illustration of elastic WLAN. Additionally, we have developed the elastic WLAN system testbed using *Raspberry Pi* [11] for APs by running hostapd [9] to evaluate the performance. *Raspberry Pi* is a card-size computer, that has the *built-in wireless network interface card (NIC)* and runs on *Linux-based Raspbian OS*, which supports the most popular *IEEE 802.11n protocol*.

In a dense WLAN, the transmission powers of the APs should be optimized to improve the communication performance, considering the capacity, the interference, and the coverage area [12–

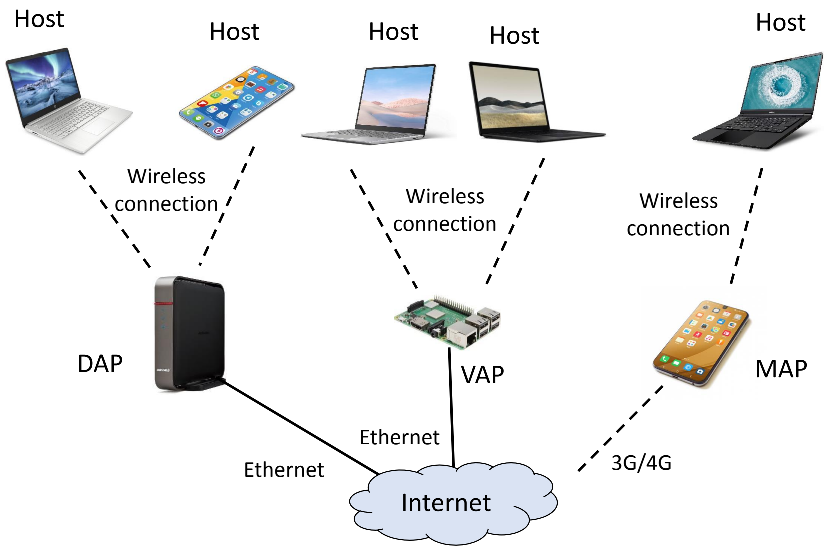


Figure 1.1: Illustration of elastic WLAN.

14]. The high transmission power of the AP may increase the capacity and coverage area, but increases the interference to other wireless devices. On the other hand, the low power can reduce the interference while limiting the capacity and area. Actually, our experiments with different transmission powers indicated that either the maximum or minimum power always gives the best performance [15]. The selection should be optimized for each AP with the consideration of the channel assignment, which is the goal of the study in this thesis.

1.2 Contributions

In this thesis, I propose the *transmission power optimization method* with channel consideration for multiple APs concurrent communications to enhance the throughput performance of WLAN.

Firstly, I propose the *transmission power optimization method* for two concurrently communicating APs in the *elastic WLAN system* to improve the throughput performance [16–19]. It selects either the maximum or minimum power for each AP such that *signal-to-interference-plus-noise ratio (SINR)* is the highest. SINR is the common metric to measure the quality of wireless communication. SINR is calculated using the *receiving signal strength (RSS)* at the receiver from the transmitter and RSS there from the interfered devices. It can represent the link capacity and the interference simultaneously by comparing the received signal and the noise at the receiver [20][21]. *Channel bonding (CB)* at $2.4GHz$ is utilized in this thesis. CB is key technology in *IEEE 802.11n* in order to enhance the link capacity by joining two adjacent $20MHz$ channels to one $40MHz$ channel [22]. The number of *orthogonal channels (OCs)* in CB is only two, *channel 1 + 5* and *channel 9 + 13*, for 13 *partially overlapping channels (POCs)* at $2.4GHz$ band. In addition, different OCs are applied for two APs. These channels are less interference to each other and may generate the best performance.

Secondly, I generalize the *transmission power optimization* with channel assignment consideration for concurrently communicating multiple APs in WLAN [23–25]. To simplify the optimization procedure and decrease the execution cost, the channels of APs are optimized before the transmission power optimization. It can avert the increasing of the number of steps for RSS measuring by considering a greater number of combinations of channels and transmission power, which may make the algorithm infeasible. In the first place, the same channel is allocated to the adjoining APs that are strongly interfered, therefore the *carrier-sense multiple access with collision avoidance (CSMA/CA)* protocol can perform properly to manage the traffic of the links [26–28]. Then, the most distant channels with the same maximum channel interval should be assigned to the other APs to reduce the interferences. After that, the transmission power is optimized by selecting the highest measured SINR. To decrease the SINR measurement load, 1) the maximum power is assigned to each AP, 2) the initial RSS from the associated host is measured, 3) the minimum power is assigned to one AP in descending order of the initial RSS, and the SINR is measured, and 4) the power combination for the highest SINR is selected.

Finally, I implement the proposed method for performance evaluations on the *elastic WLAN system testbed*, using up to four *Raspberry Pi APs*. I conduct extensive experiments in two buildings at Okayama University. The results confirm the effectiveness of the proposal.

1.3 Contents of Thesis

The remaining part of this thesis is organized as follows.

Chapter 2 introduces IEEE 802.11 wireless network technologies related to this thesis, including features of the IEEE 802.11n protocol, and software tools in the Linux operating system.

Chapter 3 reviews previous related studies.

Chapter 4 describes the experimental observations of throughput performance with different transmission powers.

Chapter 5 presents the *transmission power optimization method* for two access-points concurrent communications and the evaluations.

Chapter 6 presents the *transmission power optimization method* with channel assignment consideration for multiple access-points concurrent communications and the evaluations.

Chapter 7 reviews relevant works in literature.

Finally, Chapter 8 concludes this thesis with some future works.

Chapter 2

Background Technologies

This chapter introduces background technologies for this thesis. It overviews *IEEE802.11 WLAN technology*, *IEEE802.11n protocol* with features, and Linux tools and commands for WLANs that are used for the measurements and the implementation of elastic WLAN system.

2.1 Overview of IEEE802.11 WLAN

The *IEEE 802.11 wireless local area network (WLAN)* standard consists of *physical-layer (PHY)* and *medium-access-channel layer (MAC)*. WLAN is the development of wired LAN that allows devices to connect and communicate wirelessly [29]. WLAN is adopted in many places such as home, school, campus, and office for authorizing laptops, smartphones or other wireless devices to access Internet and communicate with each other over the air using *radio frequency (RF)* instead of wired connections.

2.1.1 Advantages of WLAN

WLAN provides many advantages over the fixed or wired networks. The following are the specific advantages of WLAN [29]:

- *User mobility:*
  Wireless networking allows mobility than wired networking. In wired networking, users need to use wired lines to stay connected to the network. WLAN gives users the ability to move around within a local coverage area and still be connected to the network.

- *Quick and easy to deploy:*
  The most obvious advantage of WLAN is that devices can connect wirelessly, eliminating the need for cables. Accordingly, the installation of WLAN can be much easier and quicker than wired LAN.

- *Expense:*
  The expense of installing and maintaining a traditional wired LAN is normally more expensive than installing and maintaining WLAN. WLAN decreases the expenses of cabling and the works related to installation and reparation. Because WLAN simplifies moving, adding, and changing, the indirect expenses of user downtime and administration are decreased.

- *Flexibility:*
  WLAN installation eliminates the need to pull cable through walls and ceilings. The network coverage area of WLAN can be easily expanded because the network medium is everywhere.

- *Scalability:*
  WLAN can be designed in various topologies needed. It can support a large number of users and large areas by adding access points to expand coverage.

2.1.2 IEEE802.11 WLAN Components

IEEE802.11 WLAN consists of four primary components as shown in Figure 2.1 [29]:

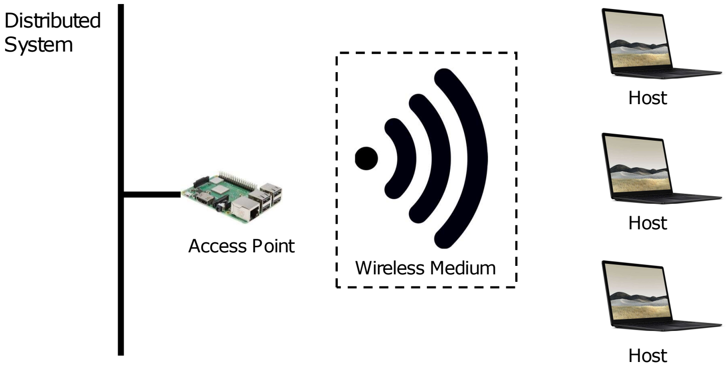


Figure 2.1: Components of IEEE802.11 WLANs.

- *Hosts or stations:*
  A host or station is one of the WLAN components. It is an electronic device that capable to access the network as equipped with wireless *network interface card (NIC)*. A host can be a desktop/laptop PC, a smartphone, or a tablet.

- *Access points (APs):*
  An AP performs as the main transmitter and receiver in WLAN that have a similar function to a switch in a wired LAN. It also acts as the hub to connect the wireless and the wired links.

- *Wireless medium:*
  The wireless medium is used in the *IEEE802.11 WLAN* standard to transfer the information/data between hosts on a network.

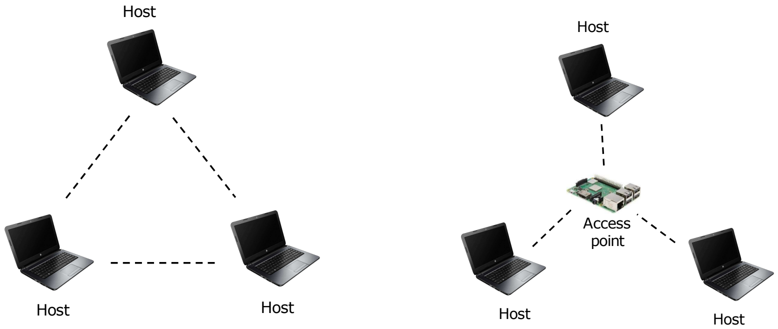
- *Distribution system:*
  A distribution system is a system that allows the interconnection of access points in an *IEEE802.11 network*. It expands a wireless network through multiple access points. The distribution system is one of WLAN components that performs as the backbone connections amongst APs. A distribution system is usually titled as the *backbone network* used to relay frames between APs. In general, *Ethernet* is applied as backbone network technology.

2.1.3 Operating Modes for IEEE802.11 WLAN

Basic service set (BSS) is the basic unit of *IEEE802.11 WLAN* that consists a set of hosts that can communicate with each other. According to BSS, there are two operating modes which are supported in *IEEE802.11* as shown in Figure 2.2.

- *Independent or ad hoc mode:*
  The first mode is *independent* or *ad hoc mode*. This mode consists a set of stations or hosts which can directly exchange their information without an AP as shown in Figure 2.2(a). It is also called as an *independent BSS (IBSS) mode*. This mode is uncommon to be implemented for permanent networks as the lack of security issues and required performances.

- *Infrastructure mode:*
  The second mode is *infrastructure mode*. In this mode, the stations send information to each other through an AP. Here, an AP performs as the main controller to all hosts in its BSS, it is called *infrastructure BSS*. Figure 2.2(b) illustrates this mode. In this mode, a host must be associated with an AP to obtain network services [30].



(a) Adhoc network. (b) Infrastructure network.

Figure 2.2: Operating modes of IEEE802.11 networks.

Further, *extended service set (ESS)* is the combination of several BSSes associated with a backbone network. Figure 2.3 illustrates the ESS. In ESS, the *service set identifier (SSID)* is provided to each AP as a "network name" for the users. All hosts in the same ESS can mutually exchange the information, even they are not in the same BSS.

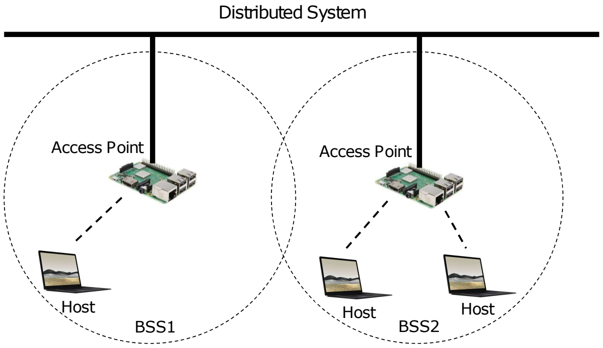


Figure 2.3: Extended service set (ESS).

2.1.4 IEEE802.11 Standards for WLAN

The *IEEE 802.11n wireless local-area network (WLAN)* is the prevalent technology globally for the Internet access. The IEEE 802.11 WLAN standard was first approved in 1997 and the second edition was released in 1999 [31,32]. This standard consists of *physical-layer (PHY)* and *medium-access-channel layer (MAC)* which operates at the *2.4-2.5GHz*, *3.6GHz* and *5.725-5.825GHz* unlicensed *Industrial, Scientific and Medical (ISM)* frequency bands determined by the ITU-R. There are some types of *IEEE Standard Association Standards*, which are available with a letter suffix, wireless standards, security aspects, *quality of service (QoS)* and others, shown in Table 2.1 [30,33–36].

Table 2.1: IEEE802.11 Standards.

Standard	**Purpose**
802.11a	Wireless network bearer operating in the 5 GHz ISM band, data rate up to $54 Mbps$
802.11b	Operate in the 2.4 GHz ISM band, data rates up to $11 Mbps$
802.11c	Covers bridge operation that links to LANs with a similar or identical MAC protocol
802.11d	Support for additional regulatory differences in various countries
802.11e	QoS and prioritization, an enhancement to the 802.11a and 802.11b WLAN specifications
802.11f	Inter-Access Point Protocol for handover, this standard was withdrawn
802.11g	Operate in 2.4 GHz ISM band, data rates up to $54 Mbps$
802.11h	Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC)
802.11i	Authentication and encryption
802.11j	Standard of WLAN operation in the 4.9 to 5 GHz band to conform to the Japan's rules
802.11k	Measurement reporting and management of the air interface between several APs
802.11l	Reserved standard, to avoid confusion
802.11m	Provides a unified view of the 802.11 base standard through continuous monitoring, management and maintenance
802.11n	Operate in the 2.4 and 5 GHz ISM bands, data rates up to $600 Mbps$
802.11o	Reserved standard, to avoid confusion
802.11p	To provide for wireless access in vehicular environments (WAVE)
802.11r	Fast BSS Transition, supports VoWiFi handoff between access points to enable VoIP roaming on a WiFi network with 802.1X authentication
802.11s	Wireless mesh networking
802.11t	Wireless Performance Prediction (WPP), this standard was cancelled
802.11u	Improvements related to ”hotspots” and 3rd party authorization of clients
802.11v	To enable configuring clients while they are connected to the network
802.11w	Protected Management Frames
802.11x	Reserved standard, to avoid confusion
802.11y	Introduction of the new frequency band, 3.65-3.7GHz in US besides 2.4 and 5 GHz
802.11z	Extensions for Direct Link Setup (DLS)
802.11aa	Specifies enhancements to the IEEE802.11 MAC for robust audio video (AV) streaming

Table 2.1: IEEE802.11 Standards.

Standard	Purpose
802.11ac	Wireless network bearer operating below 6 GHz to provide data rates of at least 1$Gbps$ for multi-station operation and 500$Mbps$ on a single link
802.11ad	Wireless Gigabit Alliance (WiGig), providing very high throughput at frequencies up to 60GHz
802.11ae	Prioritization of management frames
802.11af	WiFi in TV spectrum white spaces (often called White-Fi)
802.11ah	WiFi uses unlicensed spectrum below 1GHz, smart metering
802.11ai	Fast initial link setup (FILS)
802.11aj	Operation in the Chinese Milli-Meter Wave (CMMW) frequency bands
802.11ak	General links
802.11aq	Pre-association discovery
802.11ax	High efficiency WLAN, providing 4x the throughput of 802.11ac
802.11ay	Enhancements for Ultra High Throughput in and around the 60GHz Band
802.11az	Next generation positioning
802.11ba	Wake Up Radio
802.11bb	Light Communications
802.11bc	Enhanced Broadcast Service
802.11bd	Enhancements for Next Generation V2X
802.11be	Extremely High Throughput
802.11bf	WLAN Sensing
802.11bh	Randomized and Changing MAC Addresses
802.11me	802.11 Accumulated Maintenance Changes
802.11bi	Enhanced Data Privacy

Figure 2.4 demonstrates the current and future WiFi standards [36]. Among these standards, the common and popular ones are IEEE802.11a, 11b, 11g, 11n, 11ac, and the newest is 11ax. For the physical layer, the IEEE802.11a/n/ac adopt *Orthogonal Frequency Division Multiplexing (OFDM)* modulation scheme while the IEEE802.11b uses the *Direct Sequence Spread Spectrum (DSSS)* technology. For *IEEE802.11g*, it supports both technologies. In addition, *IEEE802.11ax* adopts *Orthogonal Frequency-Division Multiple Access (OFDMA)*. Table 2.2 summarizes the features of these common WiFi standards [29, 37–39].

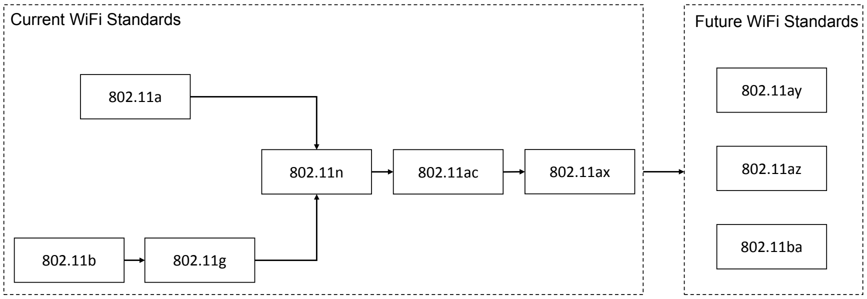


Figure 2.4: Current and future WiFi Standards.

Table 2.2: Characteristics of common IEEE802.11 standards.

	IEEE 802.11b	IEEE 802.11a	IEEE 802.11g	IEEE 802.11n	IEEE 802.11ac	IEEE 802.11ax
Release	Sep 1999	Sep 1999	Jun 2003	Oct 2009	Dec 2013	Feb 2021
Frequency Band	2.4 GHz	5 GHz	2.4 GHz	2.4/5 GHz	5 GHz	2.4/5/6 GHz
Max. Data Rate	11 Mbps	54 Mbps	54 Mbps	600 Mbps	1300 Mbps	9608 Mbps
Modulation	CCK[1] modulated with PSK	OFDM	DSSS[2], CCK, OFDM	OFDM	OFDM	OFDMA
Channel Width	20 MHz	20 MHz	20 MHz	20/40 MHz	20/40/80/160 MHz	20/40/80/160 MHz
# of Antennas	1	1	1	4	8	8
security	Medium	Medium	Medium	High	High	High

[1] CCK: Complementary Code Keying

[2] DSSS: Direct Sequence Spread Spectrum

- *IEEE802.11b: IEEE802.11b* standard was issued on September 1999. It only uses DSSS modulation technique. *IEEE802.11b* standard adopts *single-input single-output (SISO)* antenna technology. This standard operates in $2.4GHz$ band with the maximum data rate up to $11Mbps$. *IEEE802.11b* is considered as a strong system and has ability to counterbalance the same *IEEE802.11* protocols. Since there many companies have developed devices using this standard, that makes those companies competing to create the best features of the devices. The limitation of this standard is the interference among the products using *industrial, scientific and medical (ISM) band* that uses the same $2.4GHz$ band of frequency [40–42].

- *IEEE802.11a: IEEE802.11a* standard was ratified also on September 1999. This standard operates in $5Ghz$ band with a maximum data rate up to 54Mbps. OFDM coding scheme is used in this standard. This standard also adopts SISO antenna technology. There are two main limitations this standard, the compatibility matter of the 11a products with 11b products and the unavailability of 5GHz band with free of cost for all the countries in the world [40, 41, 43].

- *IEEE802.11g: IEEE802.11g* was released in 2003. IEEE suggested *IEEE802.11g* standard over *IEEE802.11a* to enhance *IEEE802.11b* technology. This standard operates at $2.4GHz$ frequency with $20MHz$ bandwidth. It introduces two modulation techniques, the *packet binary convolution code (PBCC)* and OFDM. The PBCC technique supports up to $33Mbps$ data rate while OFDM technique supports up to $54Mbps$ data rate. Compatibility matter also resolved in *IEEE802.11g* products with *IEEE802.11b* products [40, 41, 44].

- *IEEE802.11n: IEEE802.11n* standard was issued in 2009. It operates both of $2.4GHz$ and $5GHz$ ISM band *unlicensed national information infrastructure (UNII)* band. Theoretically, this standard can support data rate up to $300Mbps$. This standard employs new technology features including the use of *multiple-input multiple-output (MIMO)* antennas technology and *channel bonding (CB)* to improve the coverage range and throughput. On CB, each channel can operate with $40MHz$ bandwidth by combining two adjacent $20MHz$ channels [40,41,45,46].

- *IEEE802.11ac: IEEE802.11ac* was released on December 2013. This standard can achieve the data rate up to $1.3Gbps$. It supports static and dynamic CB up to $160MHz$ and *multi-user multiple-input multiple-output (MU-MIMO)*. This standard shows the better performance and the better coverage compared to previous *IEEE802.11* standards. This standard operates only on the $5GHz$ band [41,47–49].

- *IEEE802.11ax: IEEE802.11ax* standard was approved on February 2021 which operates in frequency bands between $1GHz$ and $7.125GHz$. The focus of this standard is to enhance the throughput-per-area or the ratio between the total network throughput and the network area. The maximum data rate of this standard is up to $9.6Gbps$. It also adopts channel bonding up $160MHz$. *IEEE802.11ax* supports *orthogonal frequency-division multiple access (OFDMA)* approach that commonly applied in cellular networks [39,50–52]. However, there are not many devices compatible with this standard.

2.2 IEEE802.11n Protocol

This section describes the *IEEE802.11n* protocol that has been used in this thesis. This protocol is commonly used in many places. This protocol adopts several enhanced features, such as MIMO, CB, and frame aggregation, over previous *IEEE802.11* protocols, 11a, 11b, 11g. Table 2.3 indicates the summary of this protocol.

Table 2.3: IEEE802.11n specification.

Specification	**IEEE802.11n**	
Frequency Band	2.4 GHz	5 GHz
Simultaneous Uninterrupted Channel	2 ch	9 ch
Available Channel	13 ch	19 ch
Max. Speed	$600Mbps$	
Max. Bandwidth	40 MHz	
Max. Spatial Streams	4	
Subcarrier Modulation Scheme	64 QAM	
Release Date	Sept 2009	

The *IEEE802.11n* supports $2.4GHz$ and $5GHz$ bands. Since the license-free band is used in WLAN, the coverage range of one AP is limited in a small area. Therefore, multiple APs are often allocated in WLAN to cover a wider area, which may cause interferences and reduce the network performance [53,54].

There is a limited number of non-interfered channels, called *orthogonal channels (OCs)* at $2.4GHz$ band of IEEE802.11n protocol. There are three OCs in $20MHz$, which are *channel 1*, *channel 7* and *channel 13*, for 13 *partially overlapping channels (POCs)*. While at 40MHz is only two OCs, they are *channel 1+5* and *channel 9+13*. Therefore, the wider the bandwidth will decrease the number of OCs. Figure 2.5 [37,55] demonstrates the channels of IEEE802.11n in 2.4 GHz band.

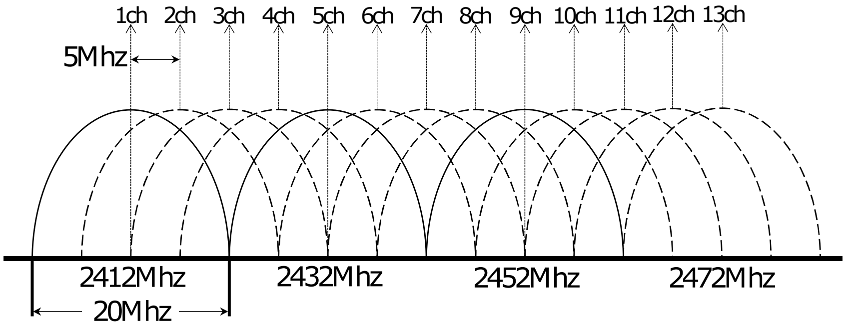


Figure 2.5: WiFi channels in 2.4 GHz band.

The *5GHz* band of *IEEE802.11n* protocol has 19 uninterrupted channels available with the 20*MHz* bandwidth. There are nine channels in the 40*MHz* bandwidth, which doubles the channel width from the 20*MHz*. In addition, there are four channels in the 80*MHz* bandwidth. Figure 2.6 shows the channels of *IEEE802.11n 5GHz band* [35, 56].

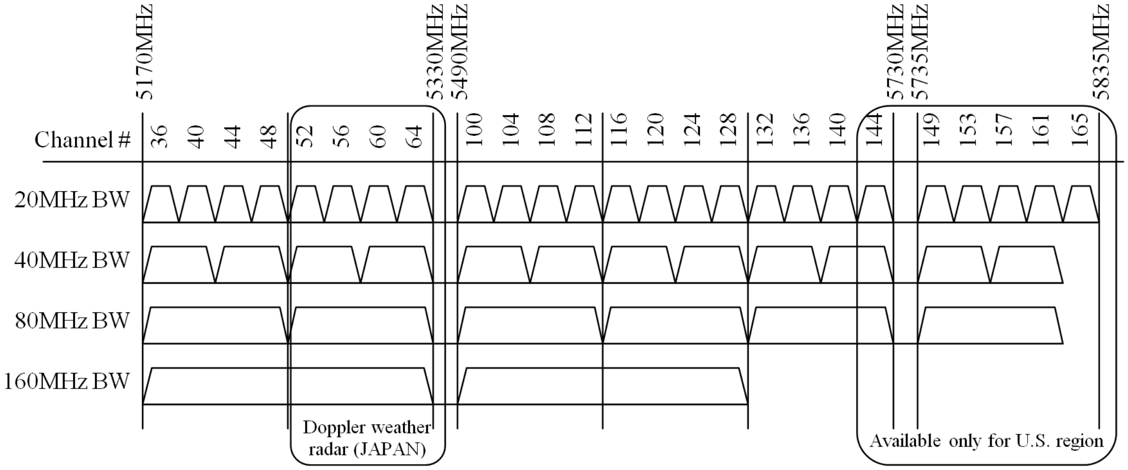


Figure 2.6: WiFi channels in 5 GHz band.

2.3 Features of IEEE802.11n Protocol

There are several new technologies in *IEEE802.11n* protocol to increase its performance. This protocol adopts several enhanced features, such as MIMO technology, channel bonding, and frame aggregation to improve the throughput. This section explains the features of *IEEE802.11n* protocol.

- *Channel Bonding:*
  Channel bonding (CB) is one of the enhanced features in *IEEE802.11n*. In CB, two adjacent 20*MHz* channels are combined as 40*MHz* channel in order to enhance the link capacity [57] as shown in Figure 2.7. It is different with the legacy 802.11a/b/g systems which can only use a single 20*MHz* channel. In the other hand, channel bonding usage can reduce the number of OCs become only two channels, they are *channel 1+5* and *channel 9+13* for 13 POCs. Table 2.4 demonstrates the usage of different channel bandwidths and spatial streams towards the throughput of *IEEE802.11n*.

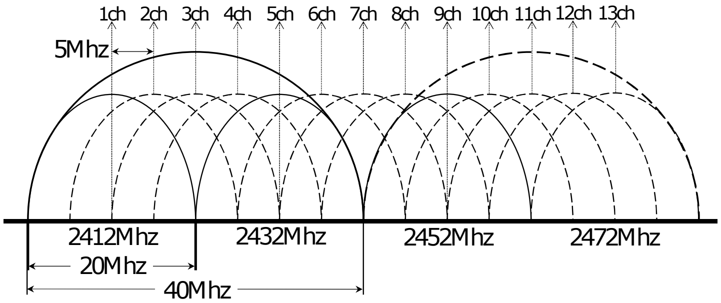


Figure 2.7: CB concept in IEEE802.11n.

Table 2.4: Effects of channel bandwidth and spatial stream's selection towards IEEE802.11n's throughput.

Stream number	Bandwidth	
	20 MHz	40 MHz
1 Stream	$72.2 Mbps$	$150 Mbps$
2 Streams	$144.4 Mbps$	$300 Mbps$
3 Streams	$216.7 Mbps$	$450 Mbps$
4 Streams	$288.9 Mbps$	$600 Mbps$

- *MIMO (Multiple-Input-Multiple-Output):*
  The other feature of *IEEE802.11n* standard is *Multiple-Input Multiple-Output (MIMO)* technology. MIMO applies multiple transmit and receive antennas to achieve high data rate in the limited bandwidth channel. This standard supports for maximum four spatial streams [58]. The performance can be enhanced over the single antenna technology in SISO. Figure 2.8 shows the comparison of SISO and 4×4 MIMO. When the *space-time block coding* (*STBC*) is adopted in the 4×4 MIMO link, the sender can transmit four copies of the data stream over four antennas to increase the reliability and the effective range of data transmissions.

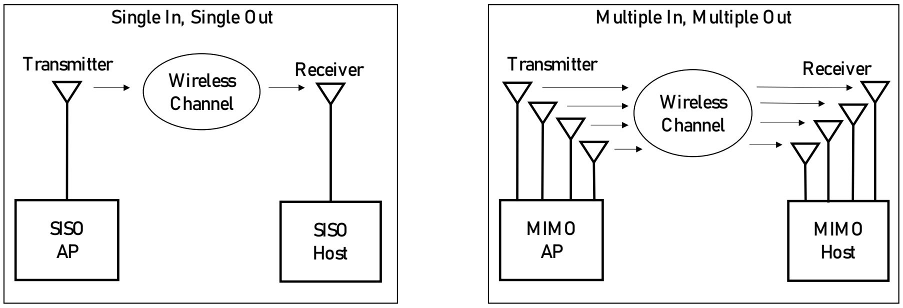


Figure 2.8: Comparison between SISO and 4×4 MIMO technology.

- *Frame Aggregation:*
  IEEE802.11n introduces the frame aggregation to enhance the performance of WLAN. The frame aggregation can transmit multiple frames by one big frame with a single pre-ample and header information to decrease the overhead by them. There are two schemes of frame aggregations, which are called *Aggregation of MAC Service Data Units (A-MSDUs)* and *Aggregation of MAC Protocol Data Units (A-MPDUs)*. The frame aggregation is a process of

packing multiple A-MSDUs and A-MPDUs together to decrease the overheads and average them over multiple frames, therefore data rate can be improved [59].

- *Modulation and Coding Scheme:*
  IEEE802.11n uses several modulations of error-correcting codes, represented by a *Modulation and Coding Scheme (MCS)*index value or *mode.IEEE802.11n* determines 31 different modes and offers the better immunity compared to selective fading via the *Orthogonal Frequency Division Multiplexing (OFDM)*. This standard boosts the number of OFDM sub-carriers of 56 (52 usable) in *High Throughput (HT)* with $20MHz$ channel width and 114 (108 usable) in HT with $40MHz$. Every sub-carrier is modulated with *BPSK*, *QPSK*, *16-QAM*, or *64-QAM*, and *Low-Density Parity-check Code (LDPC) Forward Error Correction (FEC)* coding rate of 1/2, 2/3, 3/4 or 5/6 [60].

2.4 Linux Tools for Wireless Networking

Linux is an open-source operating system which commonly used to implement new approaches, algorithms and devices in wireless network [61]. This section presents the overview of the Linux tools and software used for measurement and implementation in this thesis.

2.4.1 ’arp-scan’ - to Explore Currently Active Devices

arp-scan [62] is a command-line tool to show identity/information of the hosts in the local area network such as IP address, MAC address and vendor of the hardware used. This tool uses the ARP protocol which supports Ethernet and 802.11 wireless networks. This tool sends the ARP packet to all hosts in the local network and shows the responses from them. This tool can be installed by downloading the source code from [63] or using the following command:

```
$ sudo apt-get install arp-scan
```

Here is the command for scanning the network using *arp-scan*.

```
$ arp-scan --interface=eth0 --localnet
```

–interface=eth0 signifies the network interface to be used in scanning devices. The network interface name depends on the operating system, the network type (ethernet, wireless etc.), and the interface card type. The interface used here is *eth0* or ethernet 0. The use of *–localnet* makes *arp-scan* scan all the possible IP addresses in the network that are connected to this interface, which is defined by the interface IP address and net mask.

2.4.2 ’hostapd’ - to Make AP-mode Linux-PC

hostapd is a software activating a network interface card to act as an access point (AP) and an authentication server. Linux PC should be equipped with WLAN driver that compatible to AP mode if it is used as software AP. The *hostapd* can be installed by downloading the source code from [64] or using the following command:

```
$ sudo apt-get install hostapd
```

Here are the commands to start or stop hostapd.

```
$ sudo /etc/init.d/hostapd start
$ sudo /etc/init.d/hostapd stop
```

2.4.3 'ssh' - to Remotely Execute Command

ssh or *Secure Shell* is a network protocol that makes user can remote the computer or device securely. It adopts public-key cryptography to authenticate the remote computer [65]. There are two parts of SSH, they are *SSH client* and *SSH server*. *OpenSSH* [66] is the open source version of ssh that can be installed on Linux PC using the following command [67]:

```
$ sudo apt-get install openssh-server openssh-client
```

The following commands can be used for remotely accessing the AP through network using ssh [65,68].

```
$ ssh username@192.168.11.10
username@192.168.11.10's password:
```

Here, 192.168.11.10 represents the IP address of the AP.

2.4.4 'iw' - to Collect Information of Active Network Interface

iw [69] is a command-line Linux tool to show and modify the parameters of the network interface. *iw* is commonly installed by default in the Ubuntu distribution. It also can be installed manually using the following command:

```
$ sudo apt-get install iw
```

The following list shows the use of *iw* to display the information of the associated AP using the network interface *wlan1*:

```
$ iw dev wlan1 scan
```

2.4.5 'iperf' - to Measure Link Speed

iperf [70] is a software to measure the throughput of the network link. When conducting throughput measurement between two devices, we need to install iperf on them, one as the server mode and the other as the client mode. *Iperf* can be run in TCP and UDP protocols. There are several parameters can be adjusted in*iperf*, such as timing, buffers and protocols. iperf can be installed using the following command:

```
$ sudo apt-get install iperf
```

The *iperf* output consists of the time-stamped report of the transmitted data amount and the measured throughput. The following list indicates the use of *iperf* on the server and client side for throughput measurement:

```
$ iperf -s //server side
$ iperf -c 192.168.11.1 //client side
```

The IP address of the server is 192.168.11.1. This thesis uses *iperf* for measuring the throughput between an AP and a host through the *IEEE802.11n* standard.

2.5 Summary

This chapter presented wireless network technologies, key features of *IEEE802.11n* protocols, and Linux tools and commands that are adopted in this thesis for experiments and implementations. The next chapter will elaborate the review of previous studies in this thesis.

Chapter 3

Review of Previous Studies

This chapter reviews our previous studies of the elastic WLAN system and the implementation of the elastic WLAN system testbed using Raspberry Pi APs.

3.1 Elastic WLAN System

The elastic WLAN system has been developed to reduce the energy consumption and improve the performance by dynamically optimizing the network configuration depending on traffics and network situations.

3.1.1 Overview

WLANs have been popular deployed in many places, such as homes, companies, schools, and public areas. Therefore, unmanaged or individually controlled APs can give negative impacts on WLAN performances and energy waste issues. WLAN may face over-allocation problems due to redundant APs that have overlapping coverage areas and may have problems with overloaded hosts, which can degrade the WLAN performance. Therefore, WLANs should be flexible by dynamically adjusting the AP allocations and the associations between the APs and the hosts, depending on the network traffic demands and conditions. Thus, the elastic WLAN system would have to be studied to achieve this objective. The elastic WLAN system is designed to reduce the energy consumption and enhance the WLAN performance.

The motivations behind the study of the elastic WLAN system are summarized as follows:

1. Operational cost and energy consumption reduction:
    - Companies, educational institutions, and offices may allocate a high number of APs to provide high WLAN performances at peak times and activate these APs for the entire days. However, only a small number of APs are used during idle hours or holidays. By using the elastic WLAN system, it can resolve this problem by minimizing the number of APs by traffic demands and can reduce energy consumptions.
    - Most developing countries suffer from volatile Internet connections due to electricity supply discontinuities. By utilizing the elastic WLAN system, it can improve network performance by optimizing power usage.

2. WLAN performance improvement:
    - When the current active APs cannot cover the users, new APs should be added to ensure the WLAN performance according to the required traffic demands.
    - When the WLAN performance becomes low due to *internet service provider (ISP)* connections, power shortages, it activates the cellular networks using *mobile APs* to maintain the required WLAN performance.
    - In a dense WLAN, when the number of APs increases, interferences due to the frequency signal overlaps can increase. The elastic WLAN system can dynamically change assigned channels of APs, so it can reduce the interferences among them and enhance the WLAN performance.

3.1.2 Related Works in Literature

This section provides a brief overview of related works in literature.

In [71], Lei et al. proposed a campus WLAN framework using the *software defined network (SDN)* technology. In [72], Luengo et al. also proposed a design and implementation of a testbed for integrated wireless networks based on SDN. Although this framework is flexible to design and manage, it needs SDN-enabled devices and network virtualizations.

In [73, 74], Sukaridhoto et al. proposed a Linux implementation design using *OpenFlow* of the *fixed backoff-time switching (FBS)* method for the wireless mesh network. This requires modifications to the Linux driver kernel and specific WLAN hardware interfaces.

In [75], Ahmed et al. described the significant design issues in the preparation of a large-scale WLAN testbed for the evaluation of centralized control algorithms and presented the experimental results. They did not analyze the mechanism of energy saving and adaptive control of centralized WLANs, which is one of the major objectives of our research.

In [76], Debele et al. proposed a *Resource-on-Demand (RoD)* strategy to save energy in dense WLAN where they analyzed user behavior in the network and formulated stochastic features.

3.1.3 Design and Operational Flow

The elastic WLAN system has been designed to dynamically optimize network topology and configuration, based on network conditions. A sample system topology is presented in Figure 3.1

The implementation of the elastic WLAN system testbed uses the *management server* to manage and control the APs and the hosts by executing the *active AP configuration algorithm*. This server has the administrative access to all the devices on the network, to control the whole system through the following three steps:

1. The server explores all the devices in the network and collects the necessary information for the active AP configuration algorithm.

2. The server runs the algorithm using the inputs derived in the preceding step, where the output of the algorithm comprises the list of the active APs, the host associations, and the assigned channels.

3. The server applies the algorithm output to the network by enabling or disabling the specified APs, changing the specific host associations, and allocating channels.

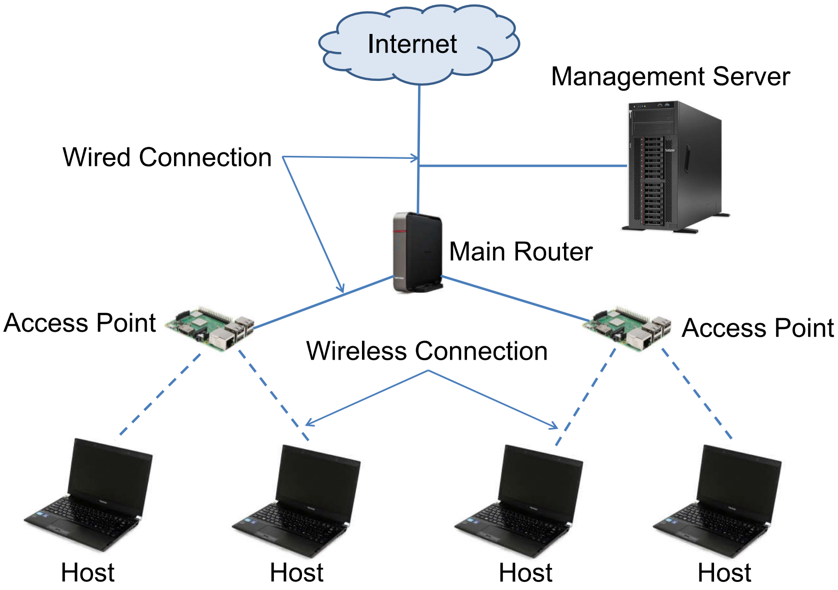


Figure 3.1: Design of Elastic WLAN system.

3.2 Testbed Implementation Using Raspberry Pi

This section describes the testbed implementation of the elastic WLAN system using Raspberry Pi and Linux PCs. As a card-size computer, *Raspberry Pi* has the *built-in wireless network interface card (NIC)* and runs on *Linux based Raspbian OS*, which supports the most popular *IEEE802.11n* protocol. By installing *hostapd* [9], it can be used as a software AP. Consequently, the use of Raspberry Pi in the elastic WLAN system is important for its distributions in developing countries.

3.2.1 Implementation Environment/Platform

As the preliminary implementation platform of the elastic wireless LAN system testbed, Linux operating system (OS) is adopted for the server, the APs, and the hosts. Linux is an open-source OS that has been used as a platform for the implementation of new algorithms, protocols, methods, and devices for advancements of wireless networks. This OS provides plenty of beneficial tools and software. Most of them are easy to configure and offer flexible use and integration with other tools [61]. Actually, *Ubuntu* is used in the implementation platform because it is the most popular distribution of the Linux environment for general-purpose users. Implementations of the elastic WLAN system on various platforms will be in future studies.

Table 3.1 identifies the devices and software that are used in the testbed implementation of the system. The *IEEE802.11n* is used for all communication links with the *channel bonding*.

3.2.2 System Topology

The simple network topology of the elastic WLAN system is illustrated in Figure 3.1. *Raspberry Pi* is used for the AP and *Linux laptop PC* is for the server and the host. The server can accomplish and control all the APs and the hosts through the administrative access to them. The APs are connected to the server through wired connections. The hosts and the APs are connected through wireless connections.

Table 3.1: Device environment and software in testbed.

AP	
model	Raspberry Pi 3 B+
CPU	Broadcom BCM2837B0 @1.4Ghz
RAM	1GB LPDDR2 SDRAM
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd
server and hosts	
model	1. Toshiba Dynabook R731/B 2. Toshiba Dynabook R734/K
CPU	1. Intel Core i5-2520M @2.5Ghz 2. Intel Core i5-4300M @2.6Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	iperf 2.0.5
main router	
model	Buffalo WZR-1750DHP

3.2.3 AP Configuration of Raspberry Pi

This section clarifies how to configure *Raspberry Pi* for AP using *hostapd* daemon [9, 10]. This device is configured as a software AP as follows:

1) Install *hostapd* software in *Raspberry Pi* by using the command:

```
$ sudo apt−get install hostapd
```

2) Configure *hostapd* using the following steps:

   i. Create the configuration file, *hostapd.conf*, inside the folder */etc/hostapd/* and assign the necessary configuration options in this file to produce the wireless network.
   ii. Start *hostapd* during the system booting, by setting the absolute path of the configuration file by editing inside the folder *etc/default/hostapd/* as:

```
DAEMON\_CONF=”/etc/hostapd/hostapd.conf”
```

   run

```
$ sudo nano etc/init.d/hostapd/
```

   and change

```
DAEMON\_CONF=/etc/hostapd/hostapd.conf
```

3) Configure the wireless connection of *Raspberry Pi* as static by editing the *”/etc/network/interfaces”* file and add the static IP address information.

4) Install the DHCP server to allow the wireless connection to automatically get the dynamic IP address by using the command:

```
$ sudo apt−get install isc−dhcp−server
```

5) Set up the DHCP server using the following procedures:
   i. Edit *dhcpd.conf* file in the folder */etc/dhcp/* and put the necessary configuration options.
   ii. Make the wireless adapter as the default for the DHCP request by editing the */etc/default/isc-dhcp-server* file as:
   INTERFACE=”wlan1”

3.3 Summary

This section reviews the study of the elastic WLAN system and its testbed implementation. The next chapter will present the experimental observations of throughput performances with different transmission powers.

Chapter 4

Experimental Observations of Throughput Performance with Different Transmission Powers

This chapter presents experimental observations of throughput performances of WLAN when the two APs are concurrently communicating using different transmission powers.

4.1 Experimental Setup

The experiments were conducted in Engineering Building #2 at Okayama University. Table 6.1 reveals the devices and software that are adopted in the experiments. Two *Raspberry Pi 3 B+* with *TP-Link TL-WN722N* NIC adapter [77] are used as the APs by running *hostapd* [9], and four *Toshiba Dynabook* laptop PCs are as the servers and the hosts. The *channel bonding* at 2.4*GHz* is applied, where *AP1* is assigned *channel 1+5* and *AP2* is *channel 9+13*. By using *Homedale* [78], it is confirmed that these channels are the least interfered ones. For use of the *channel bonding* at *Raspberry Pi 3 B+*, the following Linux commands is used:

```
ieee80211n=1
channel=1
ht_capab=[HT40+][SHORT-GI-20][SHORT-GI-40][DSSS_CCK-40][MAX-AMSDU-3839]
```

Iperf software [70] is adopted to measure the throughput by generating TCP traffics with the 477*KB* TCP window and the 8*KB* buffer. The transmission power of each AP is assigned at 0*dBm*, 5*dBm*, 10*dBm*, and 20*dBm*. For any combination of powers at the APs, TCP traffics are generated concurrently to measure the throughput. For the *Raspberry Pi* AP, the transmission power can be changed by the following command:

```
$ sudo iwconfig wlan1 txpower T
```

Here, *T* represents the value of the assigned transmission power. It can be changed from 0*dBm* to 20*dBm* in the adopted *TP-Link Wi-Fi adapter*.

Table 4.1: Device and software specifications.

AP	
model	Raspberry Pi 3 B+
CPU	Broadcom BCM2837B0 @1.4Ghz
RAM	1GB LPDDR2 SDRAM
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd
channel	1+5, 9+13
servers and hosts	
model	1. Toshiba Dynabook R731/B 2. Toshiba Dynabook R734/K
CPU	1. Intel Core i5-2520M @2.5Ghz 2. Intel Core i5-4300M @2.6Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	iperf 2.0.5

Figure 5.1 illustrates the network topology for the experiments. The connection between the server and the AP uses *Gigabit Ethernet*, and the connection between the AP and the host uses the *IEEE802.11n wireless link*.

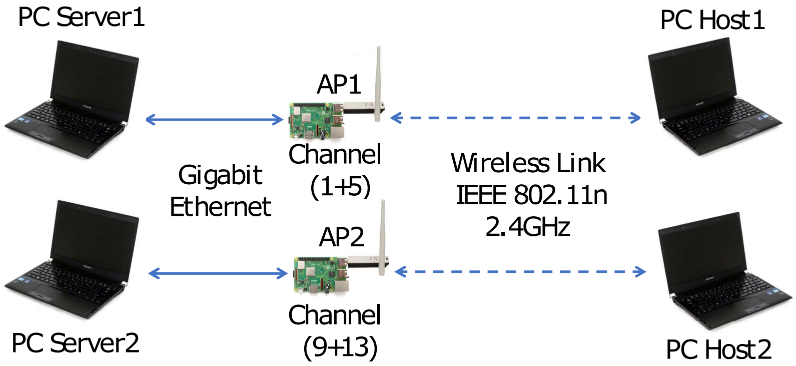
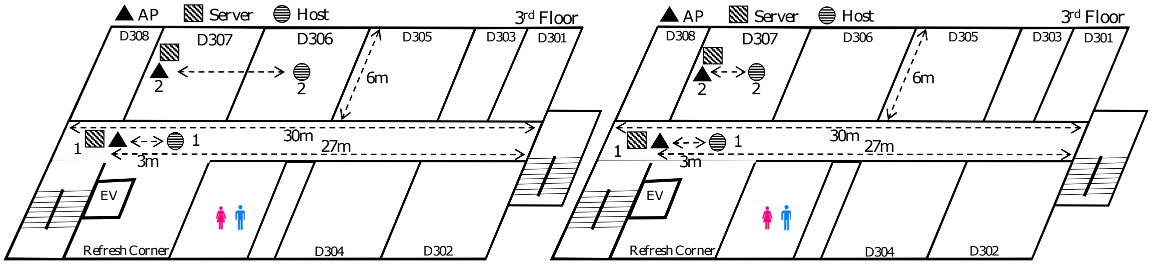
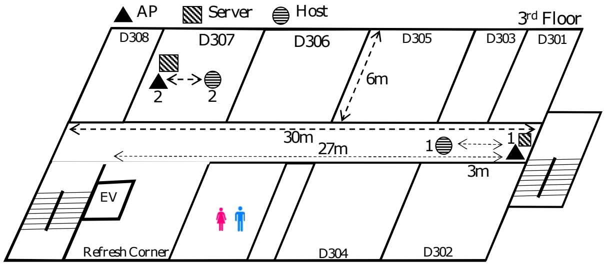


Figure 4.1: Network topology.

Figure 4.2 shows the three network topologies in the experiments. The triangle represents the *AP*, the square does the server, and the circle does the host. The room size of D306 and D307 is $7m \times 6m$, and the corridor size is $30m \times 2.3m$. In the experiments, the distance between *AP1* and *Host1* is changed from $3m$ to $27m$, and that between *AP2* and *Host2* is fixed at $3m$ in the same room and at $8m$ in different rooms.



(a) First Topology (b) Second Topology

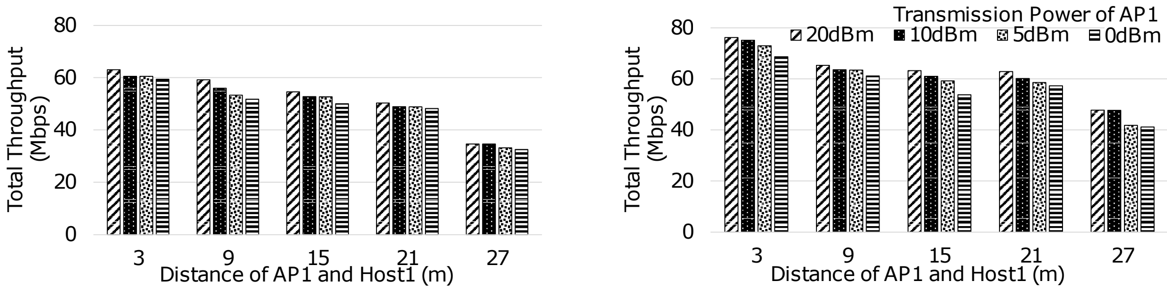


(c) Third Topology

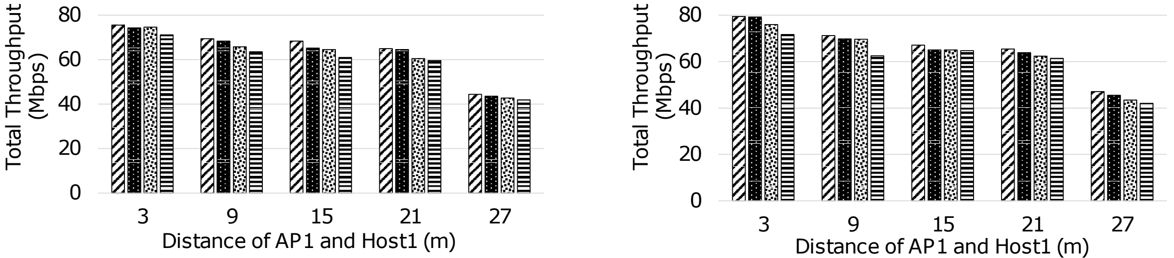
Figure 4.2: Network topologies in experiments.

4.2 Results in The First Topology

Figure 4.3 demonstrates the experiment results in the first topology. Each bar shows the total throughput of the two links. These results indicate that the best transmission power for both APs is $20dBm$ (maximum) in Figure 4.3 (d). Because there is a concrete wall between *AP2* and *Host2*, the maximum power is the best for *AP2*.



(a) Results of transmission power of AP2 = 0dBm (b) Results of transmission power of AP2 = 5dBm

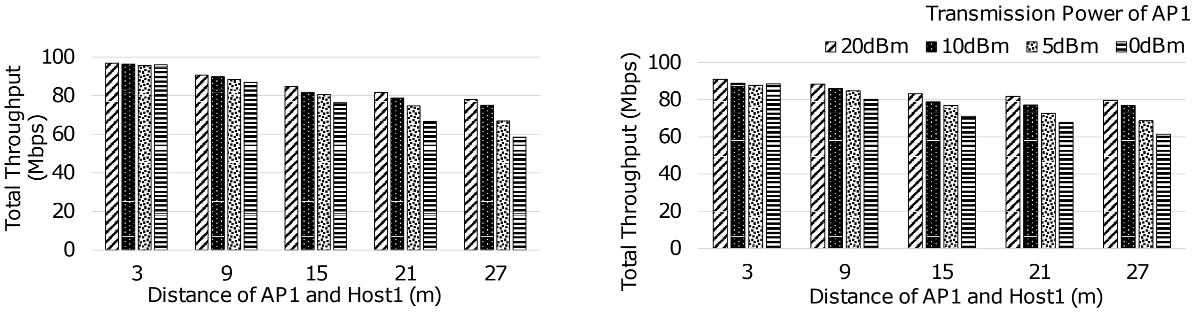


(c) Results of transmission power of AP2 = 10dBm (d) Results of transmission power of AP2 = 20dBm

Figure 4.3: Total throughput results in the first topology.

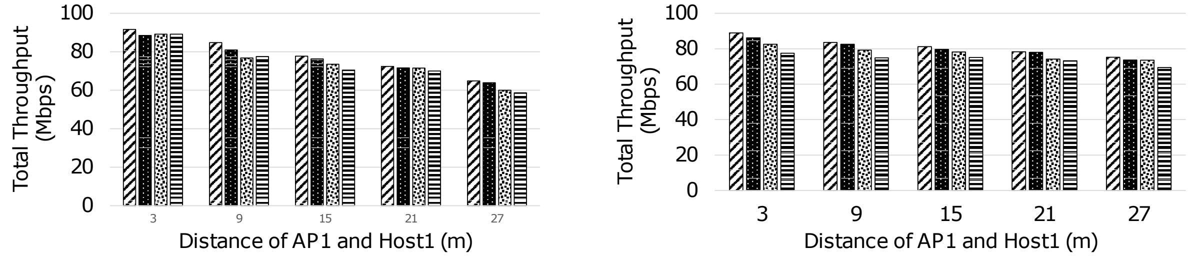
4.3 Results in The Second Topology

Figure 4.4 shows the experiment results in the second topology. The results signify that the best transmission power for *AP2* is $0dBm$ (minimum) in Figure 4.4 (a), where *AP2* and *Host2* are in the same room. The minimum power reduces the interference against *AP1*. For *AP1*, the best transmission power is $20dBm$ (maximum) at any distance.



(a) Results for transmission power 0dBm at AP2

(b) Results for transmission power 5dBm at AP2



(c) Results for transmission power 10dBm at AP2

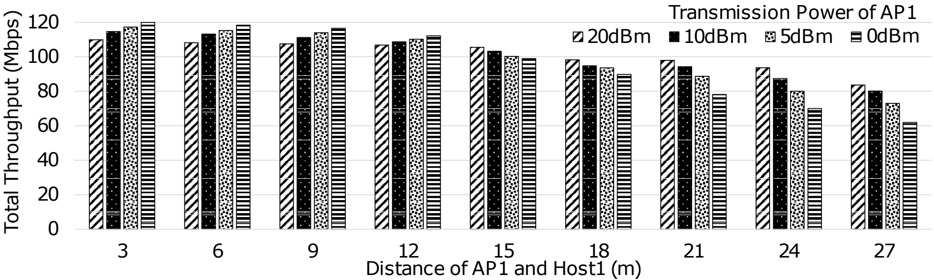
(d) Results for transmission power 20dBm at AP2

Figure 4.4: Total throughput results in the second topology.

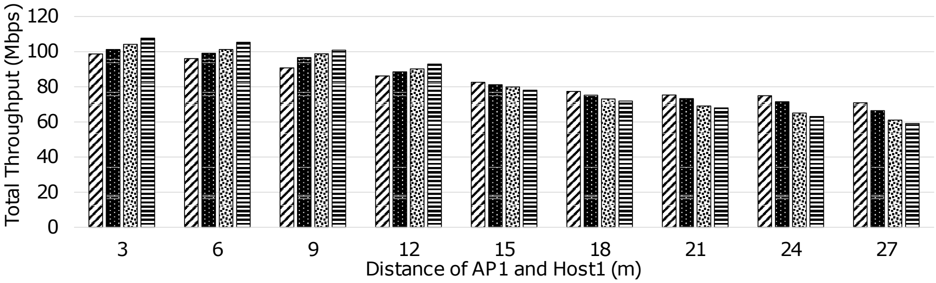
4.4 Results in The Third Topology

Figure 4.5 shows the experiment results in the third network topology. These results indicate that the total throughput is the largest among the three topologies. The best transmission power for *AP2* is $0dBm$ in Figure 4.5 (a), as *AP2* and *Host2* are in the same room. For *AP1*, $0dBm$ is best when the distance to *Host1* is $12m$ or smaller, and $20dBm$ is the best otherwise. In this topology, since the distance between two APs is much larger than that in the previous ones, the minimum transmission power for both APs may realize concurrent communications without interferences between them. However, as the distance between *AP1* and *Host1* increases, RSS at the host becomes smaller, which reduces the throughput.

Based on the results of the experiments, either the minimum transmission power or the maximum transmission power should be assigned to each AP, to maximize the throughput performance of WLAN. It is not necessary to consider the intermediate transmission power for any AP. Then, the optimal selection of either power for each AP must be studied.



(a) Results for transmission power 0dBm at AP2



(b) Results for transmission power 5dBm at AP2

Figure 4.5: Total throughput results in the third topology.

4.5 Summary

This chapter presents the experimental observations of throughput performances when the different transmission powers are assigned to two concurrently communicating APs in WLAN. They show that either the minimum or maximum transmission power should be assigned to each AP to maximize the throughput performance. The next chapter will introduce the proposal of the transmission power optimization for two concurrently communicating APs.

Chapter 5

Proposal of Transmission Power Optimization for Two Access-Points Concurrent Communications

This chapter presents the *transmission power optimization method* for two concurrently communicating APs in the WLAN.

5.1 Introduction

As discussed in Chapter 4, either the minimum or maximum transmission power should be assigned to each AP to maximize the total throughput of the WLAN. This chapter presents the transmission power optimization method for two concurrently communicating APs in WLAN. Thus, there are four combinations for the power assignments to two APs, namely, minimum & minimum, minimum & maximum, maximum & minimum, and maximum & maximum. The best combination should be selected to maximize the total throughput performance of the APs.

5.2 Idea

The proposed method first compares the *signal-to-interference-plus-noise ratio (SINR)* for the four combinations of transmission powers. Then, it selects the combination that gives the highest SINR. The SINR at two APs is actually the appropriate factor to describe the link capacity and the interference at the same time. The signal strength is related to the capacity, and the noise is related to the interference from the other links. The SINR can be easily calculated from measured *received signal strength (RSS)* at the AP that can be obtained using Linux commands *Raspberry Pi*.

In this procedure, the measured RSS can be obtained by the unit of *dBm*. Then, for the SINR calculation, the unit needs to be converted to *mW* by the following equation in [79]:

$$RSS_{mW} = 1mW \times 10^{(RSS_{dBm}/10)}. \tag{5.1}$$

5.3 Channel Assignment

In this method, the *channel bonding (CB)* is used to increase the capacity of the link at $2.4GHz$. The number of *orthogonal channels (OCs)* in CB is only two, *channel 1+5* and *channel 9+13*, for

13 *partially overlapping channels (POCs)* at 2.4*GHz* band. Usually, when two APs are assigned different OCs, they can give the best performance. For assigning the *channel 1+5*, the primary channel (*channel 1*) should be set. The following Linux commands can be used for this channel at *Raspberry Pi*:

```
ieee80211n=1
channel=1
ht_capab=[HT40+][SHORT-GI-20][SHORT-GI-40][DSSS_CCK-40][MAX-AMSDU-3839]
```

While assigning *channel 9+13*, the following Linux commands are used:

```
ieee80211n=1
channel=9
ht_capab=[HT40+][SHORT-GI-20][SHORT-GI-40][DSSS_CCK-40][MAX-AMSDU-3839]
```

5.4 Transmission Power Optimization Procedure

This section presents the procedure of selecting the best combination of the transmission powers for two APs.

5.4.1 Single Host Case

Firstly, the procedure of the transmission power optimization method for two APs with a single host is introduced. Here, it is assumed that *H1* is associated with *AP1* and *H2* is associated with *AP2*. When these links are concurrently communicating, they can cause interferences with each other. The following procedure describes the proposed transmission power optimization method:

1. Collect the MAC and IP addresses of the hosts.

2. Request the APs to assign the transmission power by selecting one of the four combinations one by one:

   - $P_{AP1} = P_{min}$ and $P_{AP2} = P_{min}$.
   - $P_{AP1} = P_{min}$ and $P_{AP2} = P_{max}$.
   - $P_{AP1} = P_{max}$ and $P_{AP2} = P_{min}$.
   - $P_{AP1} = P_{max}$ and $P_{AP2} = P_{max}$.

   where P_{AP1} and P_{AP2} represent the transmission power of *AP1* and *AP2* respectively, and $P_{min} = 0dBm$ and $P_{max} = 20dBm$ are used for *Raspberry Pi* with *TP-Link Wi-Fi adapter*.

3. Request the APs to measure the following RSS for each combination:

   - $RSS_{AP1,AP2}$: RSS at AP2 of the signal from AP1
   - $RSS_{AP2,AP1}$: RSS at AP1 of the signal from AP2
   - $RSS_{H1,AP1}$: RSS at AP1 of the signal from H1
   - $RSS_{H2,AP1}$: RSS at AP1 of the signal from H2

   - $RSS_{H1,AP2}$: RSS at AP2 of the signal from H1
   - $RSS_{H2,AP2}$: RSS at AP2 of the signal from H2
   - $aveRSS_{APx,AP2}$: average RSS at AP2 of the signal from other APs
   - $aveRSS_{APx,AP1}$: average RSS at AP1 of the signal from other APs

   where $RSS_{H1,AP1}$ and $RSS_{H2,AP2}$ represent the signal strength to transmit data, and the others become noises to them.

4. Calculate SINR for *AP1* by Eq. (5.2):

$$SINR_{AP1} = \frac{RSS_{H1,AP1}}{(RSS_{H1,AP2} + RSS_{H2,AP1} + RSS_{AP2,AP1} + aveRSS_{APx,AP1})}. \tag{5.2}$$

5. Calculate SINR for *AP2* by Eq. (5.3):

$$SINR_{AP2} = \frac{RSS_{H2,AP2}}{(RSS_{H2,AP1} + RSS_{H1,AP2} + RSS_{AP1,AP2} + aveRSS_{APx,AP2})}. \tag{5.3}$$

6. Calculate the average SINR by Eq. (5.4):

$$aveSINR = \frac{1}{2}(SINR_{AP1} + SINR_{AP2}). \tag{5.4}$$

7. Select the combination with the largest $aveSINR$ after applying the four combinations, and assign the corresponding powers, P_{AP1} and P_{AP2}, to the APs.

5.4.2 Multiple Hosts Case

The AP transmission power optimization method is extended to general cases where each AP may be associated with multiple hosts. The key of this extension is the generalization of the equation to calculate the SINR at each AP. The equations in Eq. 5.2 and Eq. 5.3 assume that only one host is associated with each AP, and the signal from the host can be interfered with the target AP.

When multiple hosts are associated with an AP, the signal from one host is transmitted intermittently by the *carrier-sense multiple access with collision avoidance (CSMA/CA)* protocol. Thus, we should consider the average of the RSS from all the hosts associated with the same AP [80]. Then, we derive the extended equations to calculate the SINR by:

$$SINR_{AP1} = \frac{\frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP1})}{(\frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP2}) + \frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP1}) + RSS_{AP2,AP1} + \frac{1}{p}\sum_{k=1}^{p}(RSS_{APx_k,AP1}))} \tag{5.5}$$

$$SINR_{AP2} = \frac{\frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP2})}{(\frac{1}{m}\sum_{j=1}^{m}(RSS_{H2_j,AP1}) + \frac{1}{n}\sum_{i=1}^{n}(RSS_{H1_i,AP2}) + RSS_{AP1,AP2} + \frac{1}{p}\sum_{k=1}^{p}(RSS_{APx_k,AP2}))} \tag{5.6}$$

where:

- $RSS_{H1_i,AP1}$: RSS at AP1 of the signal from $H1_i$
- $RSS_{H2_j,AP1}$: RSS at AP1 of the signal from $H2_j$
- $RSS_{H1_i,AP2}$: RSS at AP2 of the signal from $H1_i$
- $RSS_{H2_j,AP2}$: RSS at AP2 of the signal from $H2_j$
- $RSS_{APx_k,AP2}$: RSS at AP2 of the signal from other APs
- $RSS_{APx_k,AP1}$: RSS at AP1 of the signal from other APs

$RSS_{H1_i,AP1}$ and $RSS_{H2_j,AP2}$ represent the signal strength to transmit data, and the others become noises to them.

5.5 Evaluations with Static Hosts

This section shows the evaluations of the proposal through experiments when the hosts stay at the same locations.

5.5.1 Experiment Setup

Table 6.1 reveals the devices and software that are adopted in the experiments. *Raspberry Pi 3 B+* with *TP-Link TL-WN722N* NIC adapter [77] is used as the APs by running *hostapd* [9], and *Fujitsu* and *Toshiba* laptop PCs are as the server and the hosts.

Iperf software [70] is adopted to measure the throughput by generating TCP traffics with the $477KB$ TCP window and the $8KB$ buffer. At the same time, the RSS is measured using the following command:

```
$ sudo iw dev wlan1 scan | egrep ”(on␣wlan1)|signal:”
```

Since the measured RSS tends to fluctuate, RSS is measured 30 times with the one-second interval, and their average value is used.

For the *Raspberry Pi* AP, the transmission power can be changed to $20dBm$ by executing the following command:

```
$ sudo iwconfig wlan1 txpower 20
```

While for $0dBm$, the following command can be used:

```
$ sudo iwconfig wlan1 txpower 0
```

Figure 5.1 illustrates the network system configuration for the experiments. The connection between the router and the server and the connection between the router and the APs uses *Gigabit Ethernet*. The connection between the AP and the host uses the *IEEE802.11n wireless link*. There are several network topologies in *Engineering Building #2* and *Graduate School Building* at Okayama University are used to evaluate the proposal under various conditions.

Table 5.1: Device and software specifications.

AP	
model	Raspberry Pi 3 B+
CPU	Broadcom BCM2837B0 @1.4Ghz
RAM	1GB LPDDR2 SDRAM
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd
channel	1+5, 9+13
server PC	
model	Fujitsu Lifebook S761/C
CPU	Intel Core i5-2520M @2.5Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	iperf 2.0.5
host PC	
model	1. Toshiba Dynabook R731/B 2. Toshiba Dynabook R734/K
CPU	1. Intel Core i5-2520M @2.5Ghz 2. Intel Core i5-4300M @2.6Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	iperf 2.0.5
main router	
model	Buffalo WZR-1750DHP

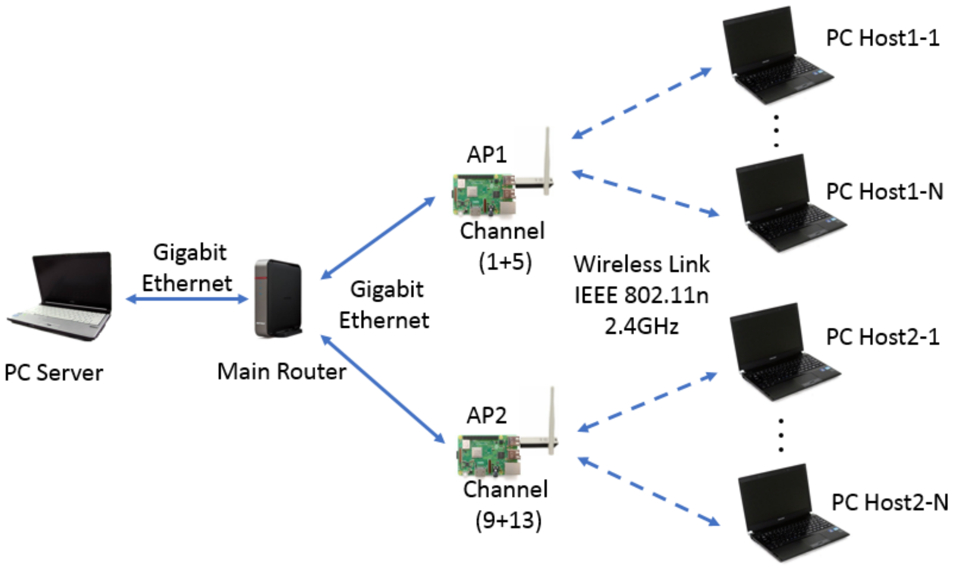


Figure 5.1: Network topology.

5.5.2 Results for Single-host Case

First, the experiment results for the single-host case are shown where each AP is connected with a single host.

5.5.2.1 First Topology

Figure 5.2 illustrates the first topology in Engineering Building #2. The room size of D307 is $7m \times 6m$ and the corridor is $30m \times 2.3m$. *AP1* and *H1* are located in the corridor, where *AP1* is near *AP2* and *H1* is moved from *H1-1* to *H1-5* position. *AP2* and *H2* are located in D307 with $3m$ distance. Both links are concurrently communicating.

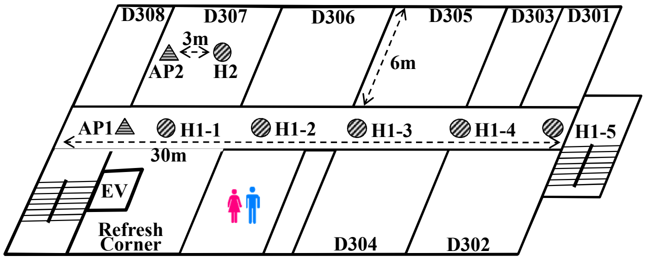


Figure 5.2: First topology with single host.

Table 5.2 indicates the average SINR and total throughput results for the four combinations of the transmission powers in the first topology. It is noticed that the proposal always selects the best combination providing the highest throughput. Here, the best power for *AP1* is the maximum and that for *AP2* is the minimum for any *H1* location. For *H1*, the strong signal can offer the higher throughput due to the longer distance. For *H2*, even the weak signal can offer the higher throughput because of the short distance between *AP2* and *H2*. Besides, the strong signal from *AP1* does not reduce the throughput of *H2*.

Table 5.2: Results for the first topology with single host.

	average SINR					total throughput (Mbps)				
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-5	H1-1	H1-2	H1-3	H1-4	H1-5
min,min	40.4	34.7	29.2	31.9	30.6	96	86.3	76.3	66.6	58.6
min,max	6.36	22.1	32.2	33.1	32.9	83.3	73.6	65	56.4	55.9
max,min	**192**	**39.7**	**45.3**	**36.2**	**33.6**	**96.9**	**90.6**	**84.6**	**81.6**	**78**
max,max	14.3	10.3	10.5	9.2	12.6	81.3	73	70.1	64.3	59.4

5.5.2.2 Second Topology

Figure 5.3 presents the second topology. Here, *AP2* and *H2* are located in the different rooms with $8m$ distance. Table 5.3 signifies that the proposal always selects the best transmission powers for both APs. In this case, the best power for *AP2* is the maximum because of the concrete wall between *AP2* and *H2*.

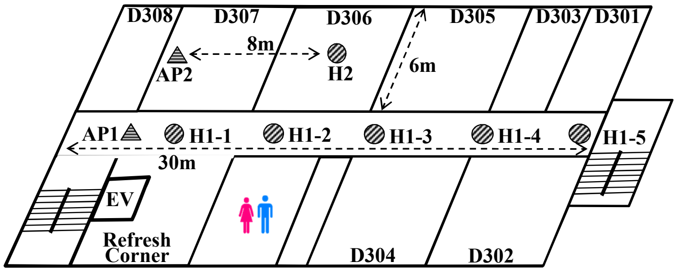


Figure 5.3: Second topology with single host.

Table 5.3: Results for the second topology with single host.

	average SINR					total throughput (Mbps)				
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-5	H1-1	H1-2	H1-3	H1-4	H1-5
min,min	19.6	1.85	0.78	0.35	0.2	59.4	51.8	50	48.2	32.6
min,max	1.93	6.8	18.5	18.4	14.4	71.7	62.5	64.8	61.4	42
max,min	71.4	73.1	35.9	28.9	24.3	63.1	59.2	54.6	50.3	34.7
max,max	**73.7**	**82.8**	**37.8**	**32.3**	**24.9**	**79.4**	**71.2**	**67.1**	**65.4**	**47.1**

5.5.2.3 Third Topology

Figure 5.4 shows the third topology. Here, *AP2* and *H2* are located in the same room, while *AP1* is located far from *AP2*. Table 5.4 indicates that the proposal always selects the best transmission powers for both APs. In this case, the best power for *AP2* is always minimum because of the short distance. On the other hand, the best power for *AP1* is minimum when *H1* is near it, and will become the maximum one when it turns out to be far.

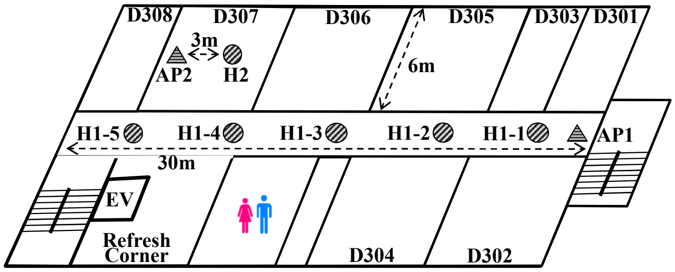


Figure 5.4: Third topology with single host.

Table 5.4: Results for the third topology with single host.

	average SINR					total throughput (Mbps)				
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-5	H1-1	H1-2	H1-3	H1-4	H1-5
min,min	**1433**	**535**	184	75.9	24.9	**119**	**116**	98	78	62
min,max	445	187	72	7.7	2.1	89	81.7	77.7	59.1	54.2
max,min	1325	516	**407**	**179**	**45.9**	109	107	**105**	**97**	**83**
max,max	736	264	105	11.5	2.43	86	83.5	82	77.7	72.9

5.5.2.4 Fourth Topology

Figure 5.5 illustrates the fourth topology. Here, *AP2* and *H2* are in the different rooms, and *AP1* is located far from *AP2*. Table 5.5 shows that the proposal always selects the best transmission powers for both APs. The best transmission power for *AP1* is the minimum one when *H1* is near and the maximum one when it becomes far. The best power for *AP2* is always the maximum one because of the wall between *AP2* and *H2*.

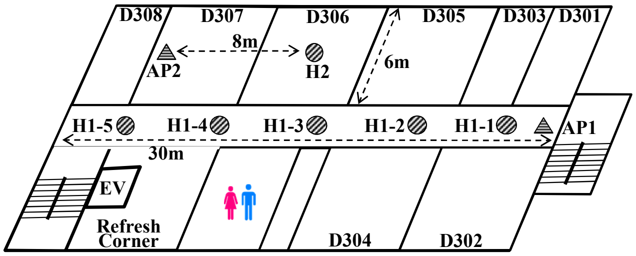


Figure 5.5: Fourth topology with single host.

Table 5.5: Results for the fourth topology with single host.

	average SINR					total throughput (Mbps)				
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-5	H1-1	H1-2	H1-3	H1-4	H1-5
min,min	157.8	15.5	2.6	0.6	0.19	64.7	47.1	32.7	30.9	27.7
min,max	**170**	**33.1**	19.2	11.4	3.09	**89.2**	**81.6**	64.7	62.2	59.6
max,min	88.1	24.9	23.4	9.8	4.9	63.4	45	39.7	36.8	31.1
max,max	92.7	29.4	**25.3**	**12.6**	**5.2**	80.1	75.9	**70.4**	**66.3**	**64.1**

5.5.2.5 Fifth Topology

Figure 5.6 shows the fifth topology in Graduate School Building. This is where *AP2* and *H2* are in the same room. *AP1* is located away from *AP2*, and *H1* is moved from *H1-1* until *H1-4*. Table 5.6 shows that the proposal always selects the best transmission powers for both APs. The best power for *AP2* is the minimum power due to the short distance between *AP2* and *H2*. On the other hand, the best power for *AP1* is minimum when up to one wall exists between *AP1* and *H1*, and is maximum when two or more walls exist.

Table 5.6: Results for the fifth topology with single host.

	average SINR				total throughput(Mbps)			
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-1	H1-2	H1-3	H1-4
min,min	**572.5**	**84.2**	56.2	14.9	**86.1**	**70.25**	46.07	44.03
min,max	520.5	73.9	46.1	14.9	85.1	61.5	44.04	47.31
max,min	543.9	53.1	**78**	**29.5**	74.32	65.05	**64.3**	**60.25**
max,max	370.8	74.9	42.7	15	76.15	56.8	56.9	57.05

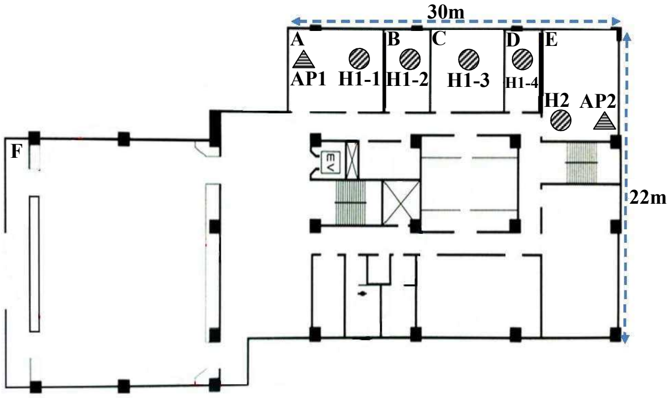


Figure 5.6: Fifth topology with single host.

5.5.2.6 Sixth Topology

Figure 5.7 illustrates the sixth topology. This is where *AP2* and *H2* are in distant locations. Again, *AP1* is located far from *AP2*, and *H1* is moved from *H1-1* until *H1-4*. Table 5.7 signifies that the proposal always selects the best transmission powers for both APs. The best transmission power for *AP2* is always the maximum one because of the long distance. The best transmission power for *AP1* is the minimum one when up to two walls exist between *AP1* and *H1*, and is the maximum one when three or more walls exist. Since *AP1* and *H2* are closely located, the weaker signal for *AP1* can reduce the interference to *H2*.

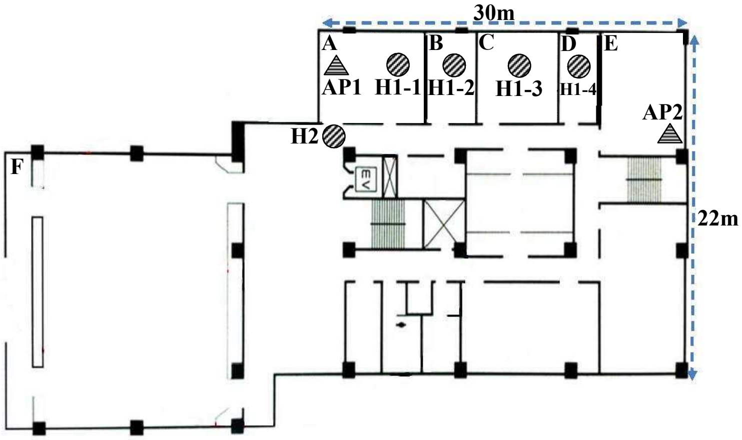


Figure 5.7: Sixth topology with single host.

Table 5.7: Results for the sixth topology with single host.

	average SINR				total throughput(Mbps)			
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-1	H1-2	H1-3	H1-4
min,min	0.63	0.02	0.01	0.01	40.77	27.6	24.04	18.67
min,max	**1.41**	**0.67**	**0.54**	0.06	**52.9**	**47.1**	**35.44**	20.21
max,min	0.79	0.04	0.02	0.03	38.07	24.62	22.34	22.03
max,max	0.82	0.08	0.06	**0.08**	48.73	46	33.93	**22.54**

5.5.2.7 Seventh Topology

Figure 5.8 shows the seventh topology. At this point, *AP2* and *H2* are closely located in the corridor, and *AP1* is close to *AP2*. *H1* is moved from *H1-1* until *H1-4* positions. Table 5.8 confirms that the proposal always selects the best transmission powers for both APs. The best power for *AP2* is the minimum one because of the short distance. The best power for *AP1* is the minimum one when *H1* exists in the same room, and is the maximum one when they are in the different rooms. Since *AP2* and *H2* are closely located, even a strong signal from *AP1* does not reduce the throughput of *H2*.

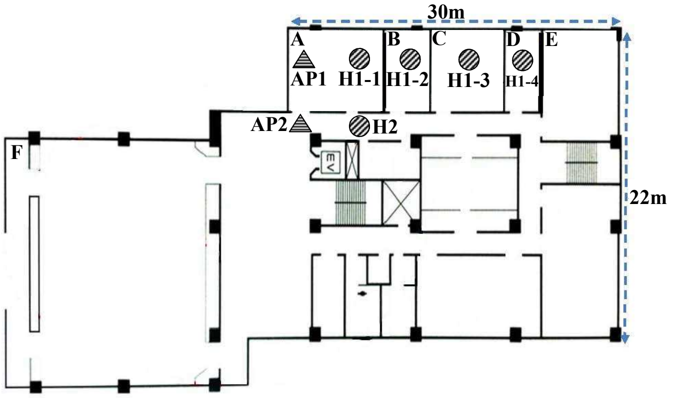


Figure 5.8: Seventh topology with single host.

Table 5.8: Results for the seventh topology with single host.

	average SINR				total throughput(Mbps)			
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-1	H1-2	H1-3	H1-4
min,min	**2.13**	0.26	0.37	0.36	**70.5**	60.26	53.03	53.6
min,max	0.91	1.11	1.26	0.79	65.4	56.13	55.3	49.47
max,min	1.52	**1.27**	**1.3**	**0.85**	63.6	**63**	**58.9**	**56.2**
max,max	0.48	0.5	0.54	0.56	59.52	58.2	56.54	52.8

5.5.2.8 Eighth Topology

Figure 5.9 shows the eighth topology. Here, *AP2* and *H2* are in the distant places, and *AP1* is located near *AP2*. *H1* is moved from *H1-1* until *H1-4*. Table 5.9 shows that the proposal always selects the best transmission powers for both APs. The best power for *AP2* is the maximum one because of the long distance. The best power for *AP1* is the minimum one when up to one wall exists between *AP1* and *H1*, and is the maximum one otherwise. The weaker signal from *AP1* can reduce the interference to *AP2*.

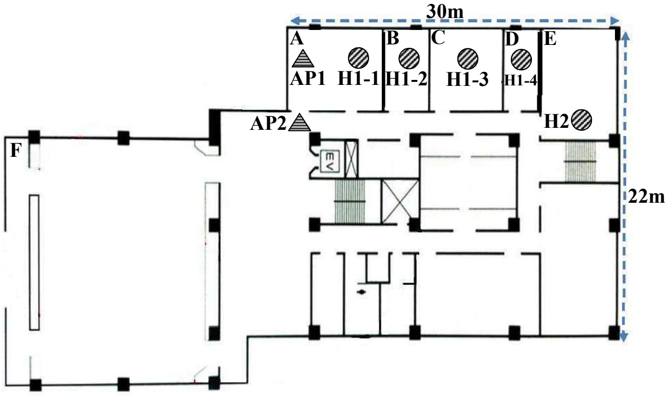


Figure 5.9: Eighth topology with single host.

Table 5.9: Results for the eighth topology with single host.

	average SINR				total throughput(Mbps)			
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-4	H1-1	H1-2	H1-3	H1-4
min,min	0.6	0.04	0.02	0.01	53.9	48.6	33.3	29.47
min,max	**1.04**	**0.59**	0.55	0.37	**68.72**	**55.4**	40.9	38.12
max,min	0.97	0.55	0.56	0.47	49.7	41.82	40.7	34.05
max,max	0.34	0.58	**0.6**	**0.61**	53.8	48	**43.43**	**41.41**

5.5.2.9 Ninth Topology

Figure 5.10 demonstrates the ninth topology. All the APs and hosts are located in the same large room. *AP1* and *AP2* are located with the largest distance in the room. *AP2* and *H2* are closely located with 3m distance. *H1* is moved from *H1-1* until *H1-3* with 3m interval. Table 5.10 shows that the best power for *AP1* is the maximum one and that for *AP2* is the minimum one. It is observed that for two APs in the same large room, one AP should adopt the maximum power and another should adopt the minimum power to improve the total throughput although the link distances are the same.

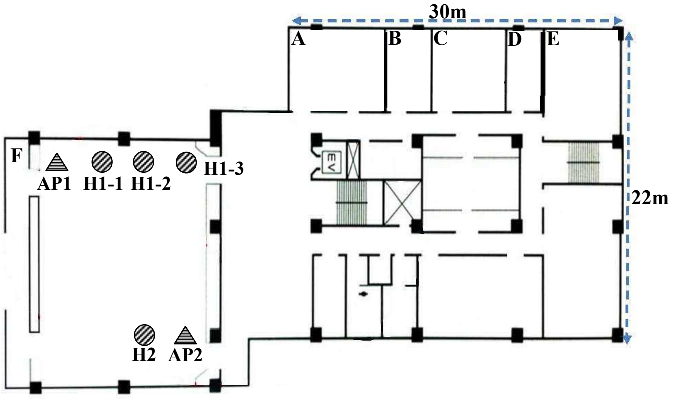


Figure 5.10: Ninth topology with single host.

Table 5.10: Results for the ninth topology with single host.

	average SINR			total throughput (Mbps)		
P_{AP1},P_{AP2}	H1-1	H1-2	H1-3	H1-1	H1-2	H1-3
min,min	0.92	1.05	0.84	67.7	62.3	52.8
min,max	1.35	1.03	0.86	63.5	53.4	50.2
max,min	**1.45**	**1.19**	**0.9**	**70.68**	**67.8**	**60.9**
max,max	1.21	1.01	0.75	66.25	61.9	56.3

5.5.3 Results for Two-Host Case

Next, the experiment results for the two-host case are shown where each AP is connected with two hosts.

5.5.3.1 First Topology

Figure 5.11 shows the first topology. The size of D307 is $7m \times 6m$ and the size of the corridor is $30m \times 2.3m$. One AP, *AP1*, and the two hosts, *H1-1* and *H1-2*, are closely located in the corridor. Another AP, *AP2*, and the two hosts, *H2-1* and *H2-2*, are located in the D307 room. *AP1* and *AP2* are located as far away as possible on this floor.

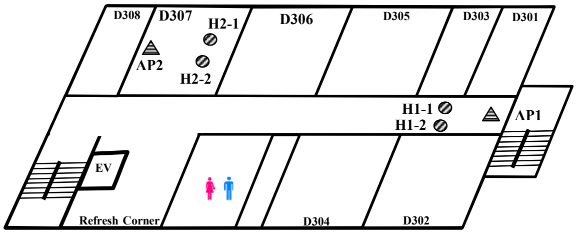


Figure 5.11: First topology with two hosts.

Table 5.11 shows the average SINR obtained from the measured RSS, and the measured total throughput results for the four combinations of the transmission powers in the first topology. The results show that the proposal selects the best combination providing the highest total throughput. Here, the best transmission powers for both APs are the minimum one because any host is closely located from the associated AP.

Table 5.11: Results for the first topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	**359.09**	**23.7**	**21**	**30.4**	**24.3**	**99.4**
min,max	337.14	22.4	21.8	23.5	23.7	91.4
max,min	347.72	24.8	20.1	24.9	24.5	94.3
max,max	325.12	22.9	23.1	21.7	22	89.7

5.5.3.2 Second Topology

Figure 5.12 shows the second topology. From the first topology, *H2-2* is moved to D306. Table 5.12 shows that the proposal selects the best transmission powers for both APs. The best power for *AP2* becomes the maximum one because one host is in a different room and the signal is attenuated by the concrete wall.

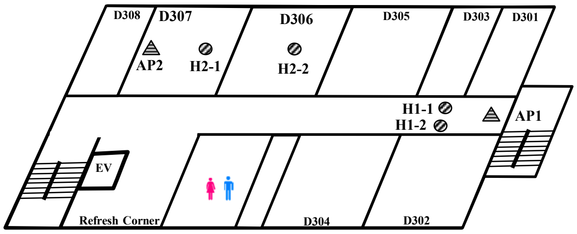


Figure 5.12: Second topology with two hosts.

Table 5.12: Results for the second topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	60.13	22.13	21.03	17.5	2.5	63.16
min,max	**326.19**	**19.74**	**22.8**	**31.97**	**4.43**	**78.94**
max,min	134.7	20.33	22.57	23.4	1.45	67.75
max,max	212.05	21.48	22.82	24.47	6.55	75.32

5.5.3.3 Third Topology

Figure 5.13 shows the third topology. From the first topology, *H2-1* and *H2-2* are moved to D306. Table 5.13 signifies that the proposal selects the best transmission powers for both APs. The best power for *AP2* again becomes the maximum one.

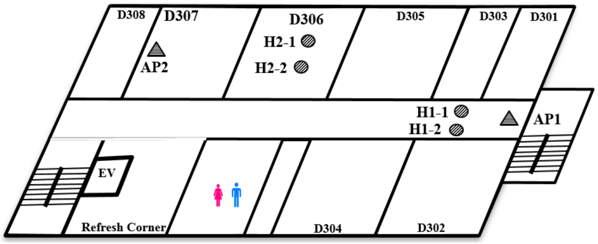


Figure 5.13: Third topology with two hosts.

Table 5.13: Results for the third topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	23.895	19.9	15.6	9.875	7.805	53.18
min,max	**30.549**	**20.95**	**17**	**16.95**	**11.755**	**66.655**
max,min	24.785	20.55	18.5	10.595	8.705	58.35
max,max	26.64	20.9	16.6	15.7	10.82	64.02

5.5.3.4 Fourth Topology

Figure 5.14 presents the fourth topology. From the first topology, *AP1*, *H1-1*, and *H1-2* are moved to the front of D307 in the corridor so that the two APs are closely located. Table 5.14 shows that the proposal selects the best transmission powers for both APs.

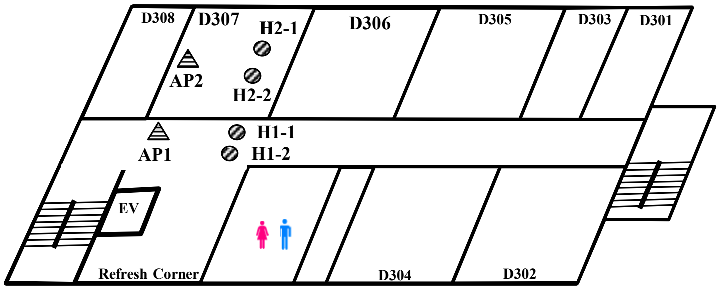


Figure 5.14: Fourth topology with two hosts.

Table 5.14: Results for the fourth topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	**8.03**	**20.6**	**18.9**	**19.8**	**19.87**	**79.17**
min,max	7.99	18.85	19.825	18.175	18.85	75.7
max,min	7.14	20.415	17.45	19.58	18.915	76.36
max,max	6.2	18.1	19.8	17.5	16.29	71.69

5.5.3.5 Fifth Topology

Figure 5.15 shows the fifth topology. From the fourth topology, *H1-2* is moved to Refresh corner. Table 5.15 indicates that the proposal selects the best transmission powers for both APs. The best power for *AP1* becomes the maximum one because *H1-2* is relatively far from it.

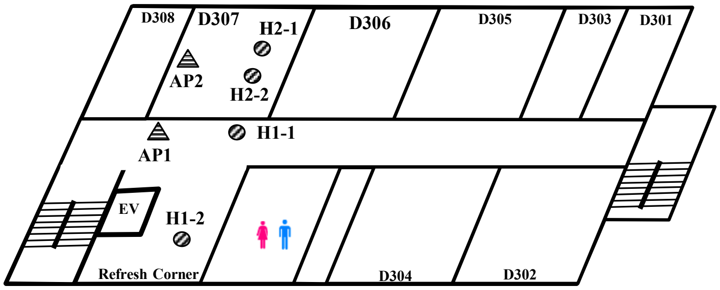


Figure 5.15: Fifth topology with two hosts.

Table 5.15: Results for the fifth topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	2.206	19	12.49	13.17	20.6	65.26
min,max	2.629	18.9	12.08	17.6	17.3	65.88
max,min	**2.896**	**27.2**	**11.57**	**15.3**	**15.637**	**69.707**
max,max	2.65	20.8	13.58	15.7	16.7	66.78

5.5.3.6 Sixth Topology

Figure 5.16 shows the sixth topology. From the fourth topology, *H2-2* is moved to D306. Table 5.16 shows that the proposal selects the best transmission powers for both APs. The best power for *AP2* becomes the maximum one because one host is in the different room.

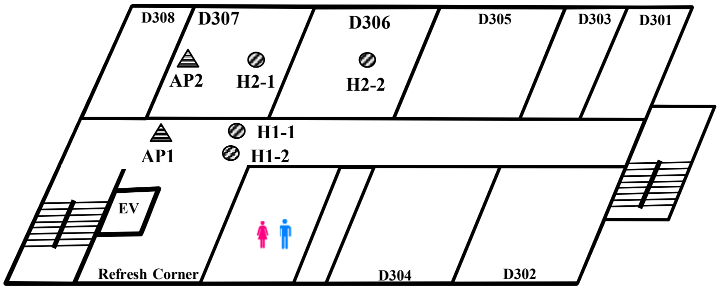


Figure 5.16: Sixth topology with two hosts.

Table 5.16: Results for the sixth topology with two hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)				
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	Total
min,min	2.73	18.68	21.3	12.4	3.16	55.54
min,max	**5.38**	**19.685**	**19.55**	**19.9**	**6.17**	**65.305**
max,min	3.79	18.23	20.77	15.1	2.82	56.92
max,max	4.54	18.975	18.79	17.15	6	60.915

5.5.4 Results for Three-Host Case

This section shows the results for the three-host case where each AP is associated with three hosts.

5.5.4.1 First Topology

Figure 5.17 shows the first topology. *AP1*, *H1*, and *H2* are closely located in the corridor, and *AP2*, *H1*, and *H2* are located in D307, where *AP1* and *AP2* are located distantly as much as possible.

Table 5.17 shows that the proposal selects the best transmission power for both APs. Here, the best powers for both APs are the minimum ones because any host is closely located from the associated AP.

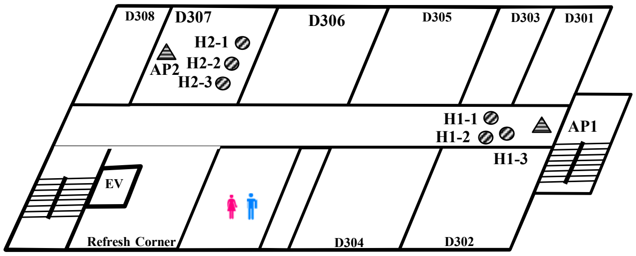


Figure 5.17: First topology with three hosts.

Table 5.17: Results for the first topology with three hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP1,H1-3	AP2,H2-1	AP2,H2-2	AP2,H2-3	Total
min,min	**2031.635**	**10.07**	**11.04**	**6.26**	**11.03**	**10.17**	**14.11**	**62.68**
min,max	1229.747	12.28	12.38	7.05	10.44	8.51	10.73	61.39
max,min	954.403	10	10.9	11.49	10.83	7.07	9.26	59.55
max,max	1314.577	9.92	12.22	10.4	6.7	10.01	9.2	58.45

5.5.4.2 Second Topology

Figure 5.18 shows the second topology. From the first topology, *H1-3* is moved in front of D306. Table 5.18 indicates that the proposal selects the best transmission powers for both APs. The best power for *AP1* becomes the maximum one because one host is far from it.

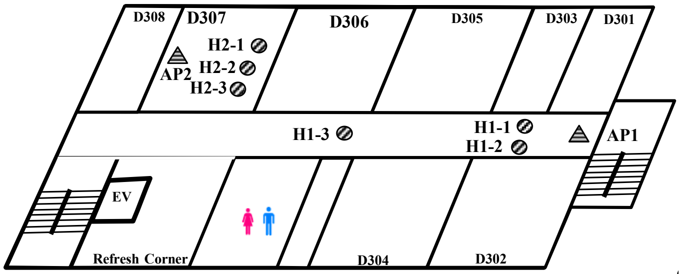


Figure 5.18: Second topology with three hosts.

Table 5.18: Results for the second topology with three hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP1,H1-3	AP2,H2-1	AP2,H2-2	AP2,H2-3	Total
min,min	145.18	15.475	10.9	6.56	7.73	4.82	5.535	51.02
min,max	1588.875	15.125	11.465	7.34	7.695	5.53	6.39	53.545
max,min	**1788.739**	**17.8**	**13.3**	**10.36**	**8.63**	**4.66**	**5.385**	**60.135**
max,max	936.718	16.5	13.6	4.53	7.5	7.19	5.32	54.64

5.5.4.3 Third Topology

Figure 5.19 shows the third topology. From the first topology, *H2-1* is moved to D308 and *H2-3* to D306. Table 5.19 indicates that the proposal selects the best transmission powers for both APs. The best power for *AP2* becomes the maximum one because two hosts are in different rooms.

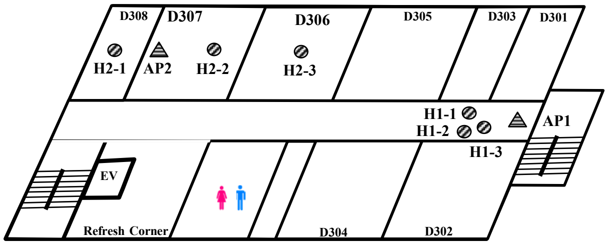


Figure 5.19: Third topology with three hosts.

Table 5.19: Results for the third topology with three hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP1,H1-3	AP2,H2-1	AP2,H2-2	AP2,H2-3	Total
min,min	132.394	8.335	10.275	5.3	6.08	6.74	5.08	41.81
min,max	**1600.168**	**9.05**	**7.8**	**11.33**	**7.72**	**8.49**	**6.64**	**51.03**
max,min	688.024	8.955	10.588	6.58	5.6225	6.455	4.44	42.64
max,max	1200.027	8.7	10.4	5.35	6.97	7.88	5.97	45.27

5.5.4.4 Fourth Topology

Figure 5.20 shows the fourth topology. From the first topology, *AP1* and the associated hosts are moved to the front of D307 in the corridor, so that both APs are closely located. Table 5.20 indicates that the proposal selects the best transmission powers for both APs.

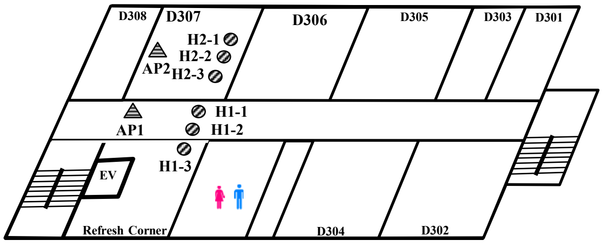


Figure 5.20: Fourth topology with three hosts.

Table 5.20: Results for the fourth topology with three hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP1,H1-3	AP2,H2-1	AP2,H2-2	AP2,H2-3	Total
min,min	**6.405**	**12.285**	**5.45**	**17.025**	**11.335**	**3.96**	**5.905**	**55.96**
min,max	4.003	10.87	7.4	10.575	10.53	5	7.055	51.43
max,min	4.68	8.005	8.625	16.58	7.96	4.54	5.875	51.585
max,max	3.47	6.6	10.335	14.33	7.54	4.745	5.905	49.455

5.5.4.5 Fifth Topology

Figure 5.21 shows the fifth topology. From the fourth topology, *H2-1* is moved to D308 and *H2-3* is to D306. Table 5.21 shows that the proposal selects the best transmission powers for both APs. The best power for *AP2* becomes the maximum one because two hosts are in different rooms.

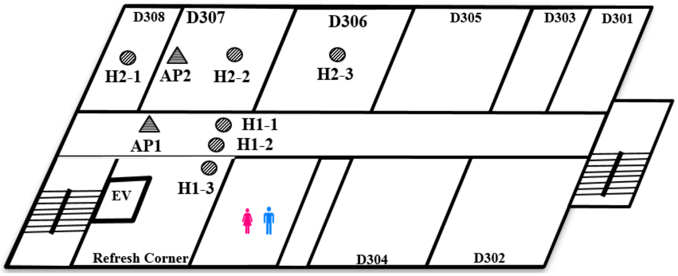


Figure 5.21: Fifth topology with three hosts.

Table 5.21: Results for the fifth topology with three hosts.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP1,H1-3	AP2,H2-1	AP2,H2-2	AP2,H2-3	Total
min,min	3.598	7.6733	9.4	8.2	4.9067	6.6867	4.5967	41.463
min,max	**6.173**	**8.7667**	**9.5867**	**4.47**	**7.5233**	**9.8733**	**6.06**	**46.28**
max,min	2.394	8.43	7.3433	7.3233	5.1433	7.82	4.3853	40.445
max,max	4.896	7.9133	7.8133	6.03	7.4433	10.12	6.5	45.82

5.6 Evaluations with Dynamic Hosts

This section shows the evaluations of the proposal through experiments when a host dynamically joins or leaves the network.

5.6.1 Experiment Setup

Engineering Building #2 at Okayama University is selected as the network field. Two topologies for AP and host locations are considered. As the dynamic host behavior, there are five cases considered; 1) both hosts join the network (*H1* and *H2* are both connected), 2) *H1* leaves the network (*H2* is connected), 3) *H1* joins the network (*H1* and *H2* are connected), 4) *H2* leaves the network (*H1* is connected), and 5) *H1* joins the network (*H1* and *H2* are connected).

5.6.2 Results

5.6.2.1 First Topology

Figure 5.22 shows the first topology with dynamic hosts. Here, *AP1* and *H1* are located in the corridor near *AP2* while *AP2* and *H2* are placed in the different rooms. Table 5.22 reveals that the proposal selects the best transmission powers for both APs in any state. It is noted that for both APs, the maximum power is selected when the corresponding host is connected with the AP, but the minimum one is selected when it is disconnected to reduce the interference.

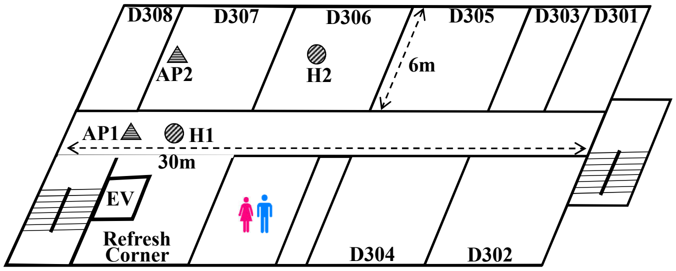


Figure 5.22: First topology with dynamic hosts.

Table 5.22: Results for the first topology with dynamic hosts.

P_{AP1}, P_{AP2}	average SINR					total throughput (Mbps)				
	H1, H2	H2	H1, H2	H1	H1, H2	H1, H2	H2	H1, H2	H1	H1, H2
min,min	19.6	0.01	17.8	21.6	18.74	59.4	14.2	59.4	50.5	59.4
min,max	1.9	**18.54**	1.84	0.38	1.84	71.7	**31.6**	71.7	48.5	71.7
max,min	71.35	0.0001	71.35	**221.4**	70.97	63.1	11.9	63.1	**55.9**	63.1
max,max	**73.72**	2.15	**74.61**	76.04	**74.35**	**79.4**	30.2	**79.4**	53.8	**79.4**

5.6.2.2 Second Topology

Figure 5.23 shows the second topology with dynamic hosts. Here, *AP1* and *H1* are closely located in the corridor, *AP2* and *H2* are located in the same room, and the distance between *AP1* and *AP2* is large. Table 5.23 shows that the proposal selects the best transmission powers for both APs at any state. It is noticed that for both APs, the minimum power is selected when both hosts are connected with the APs due to the short distances, but the maximum one is selected when the corresponding host is disconnected.

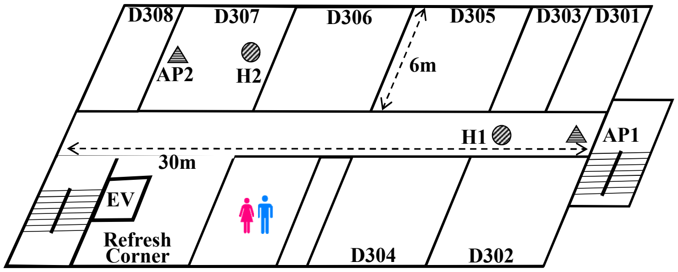


Figure 5.23: Second topology with dynamic hosts.

Table 5.23: Results for the second topology with dynamic hosts.

P_{AP1}, P_{AP2}	average SINR					total throughput (Mbps)				
	H1, H2	H2	H1, H2	H1	H1, H2	H1, H2	H2	H1, H2	H1	H1, H2
min,min	**1433.2**	754.69	**1437.23**	857.92	**1431.16**	**119**	59.5	**119**	59.4	**119**
min,max	444.97	**2032.53**	445.04	41.14	466.6	89	**59.6**	89	49.1	89
max,min	1328.4	49.5	1327.2	**2350.69**	1331.19	109	49.8	109	**59.6**	109
max,max	736.5	390.5	730.7	303.84	732.38	86	49.9	86	49.2	86

5.7 Summary

This chapter presents the *transmission power optimization method* for two concurrently communicating APs in the WLAN. The experiment results in various network topologies confirm the effectiveness of the proposed method. The next chapter will present the proposal of the *transmission power optimization method* with the channel assignment for multiple-APs concurrent communications.

Chapter 6

Proposal of Transmission Power Optimization with Channel Assignment Consideration for Multiple Access-Points Concurrent Communications

This chapter presents the generalized *transmission power optimization method* with the channel assignment consideration for any number of concurrently communicating APs in WLAN.

6.1 Introduction

In the previous chapter, I proposed the *transmission power optimization method* for two concurrently communicating APs in WLAN [17]. This method selects either the maximum or minimum transmission power for each AP such that the *signal-to-interference-plus-noise ratio (SINR)* is highest among the possible ones. The SINR is the metric to measure the quality of the wireless communication. The SINR can describe the link capacity and the interference at the same time by comparing the received signal strength and the noise level. The SINR can be calculated by the RSS at the receiver from the targeted device and interfered devices. The higher SINR indicates the higher throughput performance of WLAN as reported in [20][21].

Channel bonding (CB) is essential in IEEE 802.11n to increase the throughput performance by combining two adjacent $20MHz$ channels to become one $40MHz$ channel [22]. The number of *orthogonal channels (OCs)* in CB is only two, *channel 1+5* and *channel 9+13*, for 13 *partially overlapping channels (POCs)* at $2.4GHz$ band. When two APs are assigned different OCs, they can give the best performance.

For three or more APs, both OCs and POCs should be considered to improve the throughput performance. In [83], it has been observed that when the APs are closely located, the same OC should be assigned to them, because *carrier-sense multiple access with collision avoidance (CSMA/CA)* can manage the activations of the interfered links between them properly [84][85]. Otherwise, the different POCs with the same maximum channel interval should be assigned to the APs to reduce the interferences.

In this chapter, I propose the *joint channel assignment and transmission power optimization method* for concurrently communicating multiple APs in WLAN. Firstly, I optimize the best channel of APs by assigning the most distant channels to far APs, and the same channel to nearby APs.

I set the same channel to nearby APs in order to make CSMA/CA protocol well control links. Secondly, I optimize the transmission power by choosing either the maximum or minimum power for each AP such that it gives the best SINR.

The key point of the proposed method is the reduction of the SINR measurements. The previous method for two APs needs the SINR measurement for each possible combination of the assigned powers to the APs. When the number of APs is limited to two, the number of combinations is only four. However, if the number of APs is N, the number of combinations will be $O(2^N)$, which is infeasible for the large N.

To reduce the number of combinations for SINR measurements, first, the proposal assigns the maximum power to every AP, and measures the RSS and SINR at each AP. Then, it sequentially selects the AP that will be changed to the minimum power, in descending order of the measured RSS. After every AP is selected and SINR is obtained, the combination of the powers giving the largest SINR is selected as the best transmission power. Thus, this method can reduce the number of SINR measurements to $O(N)$.

6.2 Channel Assignment Optimization Procedure

The proposed method adopts *channel bonding (CB)* to enhance the throughput performance of the WLAN. CB combines two adjacent $20MHz$ channels into one $40MHz$ channel [82]. Therefore, *channel 1+5* and *channel 9+13* become the *orthogonal channels (OCs)* when 13 *partially overlapping channels (POCs)* are available.

In the channel assignment, when the WLAN has two APs, the two different OCs are assigned them. Likewise, when the WLAN has three or more APs, both OCs and POCs are considered. For the APs that are closely located, the same OC is assigned to them so that the *carrier-sense multiple access with collision avoidance (CSMA/CA)* protocol performs properly [83][84][85]. For the other APs, the different POCs with the same maximum channel interval are assigned to reduce the interferences among them. The following procedure describes the channel assignment optimization.

1. Assign the different POCs with the same maximum channel interval to the APs.
2. Assign the maximum transmission power for each AP.
3. Measure RSS at AP_p from AP_q, RSS_{AP_p,AP_q}, for $p \neq q$.
4. Sort the RSS_{AP_p,AP_q} in descending order.
    (a) Select two APs that have the highest RSS_{AP_p,AP_q} where at least one AP is not assigned an OC.
    (b) If $RSS_{AP_p,AP_q} > RSS_{AP_{threshold}}$, assign the same OC to them.
5. Assign the different POCs from the assigned OCs with the same maximum channel interval to the remaining APs if they exist.
6. If one OC is not assigned to any AP, assign it to the last AP that was assigned another OC.

The threshold $RSS_{AP_{threshold}}$ should be properly given to detect the closely located APs. In this method, $RSS_{AP_{threshold}} = -60dBm$ is adopted and selected by extensive experiments.

6.3 Transmission Power Optimization Procedure

The following procedure describes the proposed AP transmission power optimization method.

1. Assign the maximum transmission power for each AP.
2. Measure the *RSS* at each AP from the associated hosts and the *SINR* considering any interfering AP and host. The *SINR* for AP_p in the WLAN is calculated by Eq. (6.1).

$$SINR_{AP_p} = \frac{\frac{1}{n_p}\sum_{i=1}^{n_p}(RSS_{H_{p,i},AP_p})}{\sum_{\substack{q=1\\q\neq p}}^{m} RSS_{AP_q,AP_p} + \sum_{\substack{q=1\\q\neq p}}^{m}\frac{1}{n_q}\sum_{i=1}^{n_q} RSS_{H_{q,i},AP_p} + \sum_{\substack{q=1\\q\neq p}}^{m}\frac{1}{n_p}\sum_{i=1}^{n_p} RSS_{H_{p,i},AP_q} + \sum_{x\in IAP_{AP_p}} RSS_{AP_x,AP_p}} \tag{6.1}$$

   n_p represents the number of hosts associated with AP_p, $H_{p,i}$ does the i-th associated host, $RSS_{H_{p,i},AP_p}$ does the RSS at AP_p from $H_{p,i}$, IAP_{AP_p} does the set of unknown APs that are interfered with AP_p.

3. Calculate the average SINR for all the APs by Eq. (6.2).

$$aveSINR = \frac{1}{m}\sum_{p=1}^{m}(SINR_{AP_p}) \tag{6.2}$$

4. Sort the APs in descending order of *RSS* and make the sorted list of the APs.
5. Select the first AP in the list and assign the minimum power to the AP.
6. Measure the *RSS* and calculate *SINR* at every AP.
7. Calculate the average SINR for all the APs.
8. If the average SINR becomes smaller than the previous one, select the previous combination of transmission powers to the APs and terminate the procedure.
9. Remove the selected AP from the sorted list and go to 5.

For the *Raspberry Pi* AP, the RSS can be measured by executing the following command:

```
$ sudo iw dev wlan1 scan | egrep ’’(on wlan1)|signal:’’
```

Since the measured RSS tends to fluctuate, the RSS is measured 30 times with the one-second interval, and their average value is used. By running this command, it can show all RSS from devices. By checking the MAC Address, it can classify which is the received signal or interfering signal.

It is noted that the measured RSS in *dBm* is converted to the one in *mW* for the SINR calculation by:

$$RSS_{mW} = 1mW \times 10^{(RSS_{dBm}/10)}. \tag{6.3}$$

6.4 Evaluations

This section shows the evaluation of the proposal in several topologies up to four-APs case. Each AP is associated with a single host or two hosts.

6.4.1 Experiment Setup

The experiments use *Raspberry Pi 3 B+* [11] with *TP-Link TL-WN722N wireless NIC adapter* [77] for the APs by running *hostapd* [9], and *Fujitsu* and *Toshiba* laptop PCs for the server and hosts. Table 6.1 displays the details of devices and software in the experiments. *Iperf software* [70] is adopted to measure the throughput by generating TCP traffics with the $477KB$ TCP window and the $8KB$ buffer. At the same time, the RSS is measured by *iw commands*. The channel bonding is assigned at *Raspberry Pi 3 B+* by using the following Linux commands:

```
ieee80211n=1
channel=1
ht_capab=[HT40+][SHORT-GI-20][SHORT-GI-40][DSSS_CCK-40][MAX-AMSDU-3839]
```

Table 6.1: Device and software specifications.

access point	
model	Raspberry Pi 3 B+
CPU	Broadcom BCM2837B0 @1.4Ghz
RAM	1GB LPDDR2 SDRAM
NIC chipset	Atheros AR9002U
Operating System	Linux Raspbian
software	hostapd
server PC	
model	Fujitsu Lifebook S761/C
CPU	Intel Core i5-2520M @2.5Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	Iperf 2.0.5
host PC	
model	1. Toshiba Dynabook R731/B 2. Toshiba Dynabook R734/K
CPU	1. Intel Core i5-2520M @2.5Ghz 2. Intel Core i5-4300M @2.6Ghz
RAM	4GB DDR3 1333MHz
Operating System	Linux Ubuntu 14.04 LTS
software	Iperf 2.0.5

Here, the throughput is measured by generating downlink TCP traffics from the AP (server) to the host using *iperf* software. Downlink TCP traffics are common since users often download data from servers to hosts using TCP at Web site accesses. Jeong et al. in [86], and Kim et al. in [87] showed that the traffics in most wireless multimedia applications are not symmetric toward downlinks (from APs to hosts), compared to uplinks (from hosts to APs). Large files will sometimes be transmitted at downlinks, where very short commands *(bytes)* are transmitted at uplinks. Thus, they claimed that downlinks should be allocated more bandwidth than uplinks.

Figure 6.1 illustrates the testbed system. This server dynamically collects the information of the associated hosts from every AP and the RSS. Then, when it finds a new host, it optimizes the channel assignments and the transmission powers of the APs by running the proposed algorithm. The connection between the router and the server and the connection between the router and the APs uses *Gigabit Ethernet*. The connection between the AP and the host uses the *IEEE802.11n wireless link*.

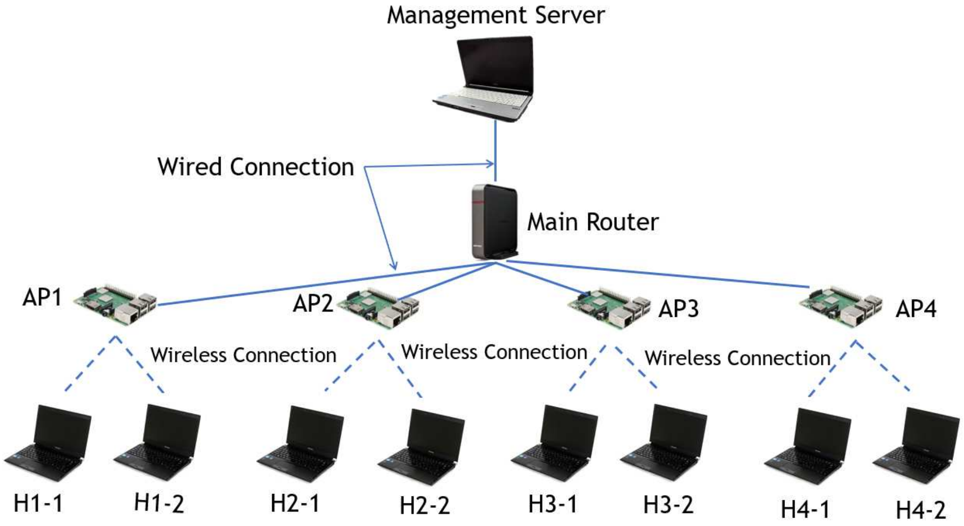


Figure 6.1: Testbed System.

There are several topologies in *Engineering Building #2* at Okayama University that are used to evaluate the proposal under various conditions. Figure 6.2 illustrates the network fields while Table 6.2 demonstrates the experiment scenarios in this evaluation.

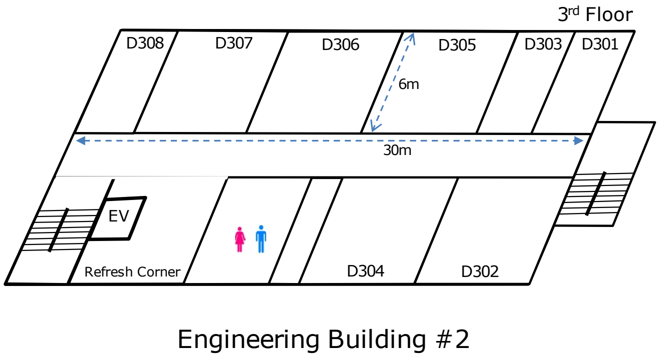


Figure 6.2: Network field.

Table 6.2: Experiment scenarios

Case	Topology	AP1 Location	H1-1 Location	H1-2 Location	AP2 Location	H2-1 Location	H2-2 Location	AP3 Location	H3-1 Location	H3-2 Location	AP4 Location	H4-1 Location	H4-2 Location
Two-APs	1	In front of D301	In front of of D301	-	D307	D307	-	-	-	-	-	-	-
	2	In front of D301	In front of D306	-	D307	D307	-	-	-	-	-	-	-
	3	In front of D301	In front of D303	-	D307	D306	-	-	-	-	-	-	-
	4	In front of D301	In front of D306	-	D307	D306	-	-	-	-	-	-	-
Three-APs	1	D307	D307	-	In front of D308	In front of D307	- -	In front of D301	In front of D301	-	-	-	-
	2	D307	D306	-	In front of D308	In front of D307	- -	In front of D301	In front of D301	-	-	-	-
	3	D307	D307	-	In front of D308	Refresh Corner	- -	In front of D301	In front of D301	-	-	-	-
	4	D307	D306	-	In front of D308	In front D307	- -	In front of D301	In front of D306	-	-	-	-
	5	D307	D307	-	In front of D308	Refresh Corner	- -	In front of D301	D306	-	-	-	-
	6	D307	D306	-	In front of D308	Refresh Corner	- -	In front of D301	In front of D306	-	-	-	-
	7	D307	D307	D307	Refresh Corner	Refresh Corner	Refresh Corner	In front of D301	In front of D303	In front of D303	-	-	-
	8	D307	D307	D308	Refresh Corner	Refresh Corner	Refresh Corner	In front of D301	In front of D303	In front of D303	-	-	-
	9	D307	D307	D307	Refresh Corner	Refresh Corner	In front of D306	In front of D301	In front of D303	In front of D303	-	-	-
	10	D307	D307	D307	Refresh Corner	Refresh Corner	In front of D306	In front of D301	In front of D303	D306	-	-	-
	11	D307	D307	D306	Refresh Corner	Refresh Corner	In front of D308	In front of D301	In front of D303	In front of D306	-	-	-
Four-APs	1	D307	D307	-	In front of D308	In front of D308	- -	In front of D301	In front of D303	- -	Refresh Corner	Refresh Corner	-
	2	D307	D308	-	In front of D308	In front of D308	- -	In front of D301	In front of D303	- -	Refresh Corner	Refresh Corner	-
	3	D307	D308	-	In front of D308	In front of D306	- -	In front of D301	In front of D303	- -	Refresh Corner	Refresh Corner	-
	4	D307	D308	-	In front of D308	In front of D306	- -	In front of D301	In front of D306	- -	Refresh Corner	Refresh Corner	-
	5	D307	D307	D307	In front of D308	In front of D308	In front of D308	In front of D301	In front of D303	In front of D303	Refresh Corner	Refresh Corner	Refresh Corner
	6	D307	D307	D308	In front of D308	In front of D308	In front of D306	In front of D301	In front of D303	In front of D306	Refresh Corner	Refresh Corner	In front of D306

6.4.2 Results for Two-AP Case

This section shows the results for all topologies in the two-AP case. Since each topology has only two APs, two different OCs are assigned to the APs. Based on the results, the proposed method always selects the best transmission powers for each AP.

6.4.2.1 First Topology

In the first topology, *AP1* is located in front of D301, *H1* is in front of D303, *AP2* and *H2* are in D307. Table 6.3 reveals the average SINR obtained from the measured RSS, and the measured total throughput results in the first topology. Here, the best transmission for each AP is minimum power since the host is located near the AP. The minimum power can decrease the interference while giving the high data rate using the high-rate modulation coding scheme (MCS).

Table 6.3: Results for the first topology with two APs.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)		
		AP1,H1	AP2,H2	Total
max,max	736.47	52.6	33.9	86.5
min,max	1324.8	56.7	53.2	109.9
min,min	**1433**	**60.5**	**58.5**	**119**

6.4.2.2 Second Topology

Table 6.4 demonstrates the results for the second topology. From the first topology, *H1* is moved to the front of D306. The best transmission power for *AP1* becomes maximum power because the host is far from *AP1*. The maximum power is necessary to prevent the throughput drop by the distance loss of the signal.

Table 6.4: Results for the second topology with two APs.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)		
		AP1,H1	AP2,H2	Total
max,max	107.01	47.6	34.4	82
max,min	**407**	**56.4**	**48.6**	**105**
min,min	199.9	50.25	48.65	98.9

6.4.2.3 Third Topology

The results of the third topology are illustrated in Table 6.5. From the first topology, *H2* is shifted to D306. In this topology, the best transmission power for *AP2* becomes maximum because of the concrete wall between *AP2* and *H2*. The maximum power is necessary to prevent the throughput drop by the signal attenuation at the concrete wall.

Table 6.5: Results for the third topology with two APs.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)		
		AP1,H1	AP2,H2	Total
max,max	92.7	51.3	28.8	80.1
min,max	**170**	**50.9**	**38.3**	**89.2**
min,min	57.8	50.1	14.6	64.7

6.4.2.4 Fourth Topology

Here, the location of *H1* is changed to the front of D306, from the third topology. Table 6.6 displays the results for the fourth topology. Here, the best transmission power for *AP1* becomes maximum power because the host is far from *AP1*. The maximum power provides sufficient signal for the host which is far.

Table 6.6: Results for the fourth topology with two APs.

P_{AP1},P_{AP2}	average SINR	throughput (Mbps)		
		AP1,H1	AP2,H2	Total
max,max	**25.3**	**39.8**	**30.6**	**70.4**
min,max	19.24	34.3	30.4	64.7
min,min	2.62	28.9	3.8	32.7

6.4.3 Results for Three-AP Case

This section shows the results for the Three-AP case. Three APs are located in the different rooms. The three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to the APs. Based on the results, the proposed method always selects the best transmission powers for all APs.

6.4.3.1 First Topology

In the first topology, *AP1* and *H1* are closely located in D306. *AP2* and *H2* are located in front of D308. *AP3* and *H3* are located in front of D302. Table 6.7 demonstrates the results for the first topology. Because any host is near the AP, the best transmission power for any AP is the minimum one to reduce the interference while providing the high data rate using the high-rate MCS.

Table 6.7: Results for the first topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	90.567	35.3	8.2	29.1	72.6
min,max,max	114.829	39.2	20	18	77.2
min,min,max	222.584	38.6	13	28.8	80.4
min,min,min	**331.807**	**36.4**	**9.3**	**35.6**	**81.3**

6.4.3.2 Second Topology

Table 6.8 shows the results for the second topology. From the first topology, *H1* is moved to D306. The best transmission power for *AP1* becomes the maximum one because the host is located in a different room. The maximum power is necessary to avoid the throughput drop caused by the signal attenuation at the wall.

Table 6.8: Results for the second topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	76.915	10.3	14.3	28.9	53.5
max,min,max	94.221	11.4	14.1	33.52	59.02
max,min,min	**216.915**	**12.8**	**14.7**	**36.76**	**64.26**
min,min,min	42.036	3.54	13.26	28.19	44.99

6.4.3.3 Third Topology

In the third topology, from the first topology, the location of *H2* is moved to the Refresh Corner. The results of this topology are displayed in Table 6.9. The best transmission power for *AP2* becomes the maximum one because the host is relatively far from it. The maximum power is necessary to avoid the throughput drop caused by the distance loss of the signal.

Table 6.9: Results for the third topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	60.163	17.24	10.1	29.32	56.66
min,max,max	75.536	18.96	12.35	31.79	63.1
min,max,min	**106.15**	**20.14**	**13.27**	**32.56**	**65.97**
min,min,min	38.591	16.81	10.05	28.98	55.84

6.4.3.4 Fourth Topology

Table 6.10 reveals the results of the fourth topology. Here, the location of *H3* is shifted to the front of D306, from the second topology. In this topology, the best power for *AP3* becomes the maximum one because the host is far from it. The maximum power gives enough signal for the host which is far.

Table 6.10: Results for the fourth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	53.766	28.77	10.13	13.37	52.27
max,min,max	**68.587**	**30.5**	**12.7**	**15.1**	**58.3**
max,min,min	39.821	30.11	10.19	6.41	46.71
min,min,min	18.365	18.92	8.04	3.94	30.9

6.4.3.5 Fifth Topology

Table 6.11 demonstrates the results for the fifth topology. From the third topology, the location of *H3* is changed to D306. Here, the best power for *AP3* becomes the maximum one because the host is far from it. The maximum power provides sufficient signal for the host which is far.

Table 6.11: Results for the fifth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	32.587	19.92	11.4	19.41	50.73
min,max,max	**43.44**	**22.4**	**13.92**	**21.78**	**58.1**
min,min,max	22.158	17.18	8.91	17.18	43.27
min,min,min	11.603	13.56	5.12	14.79	33.47

6.4.3.6 Sixth Topology

The results for the sixth topology are shown in Table 6.12. From the fourth topology, *H2* is moved to the Refresh corner. In this topology, the best power for *AP2* becomes the maximum one because the host is far from it. The maximum power can avoid the throughput drop caused by the distance loss of the signal.

Table 6.12: Results for the sixth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)			
		AP1,H1	AP2,H2	AP3,H3	Total
max,max,max	**2.7891**	**17.83**	**9.14**	**18.06**	**45.03**
max,max,min	2.255	15.91	7.46	13.76	37.13
max,min,min	1.208	14.65	5.19	12.84	32.68
min,min,min	1.158	13.13	3.72	10.54	27.39

6.4.3.7 Seventh Topology

In the seventh topology, each AP is associated with two hosts. *AP1*, *H1-1*, and *H1-2* are closely located in D307. *AP2*, *H2-1*, and *H2-2* are located in the Refresh corner. *AP3*, *H3-1*, and *H3-2* are located in front of D302. Table 6.13 presents the results for the seventh topology. Here, each AP is associated with two hosts. The best transmission power for all APs are the minimum one because any host is closely located with the associated AP. The minimum power can reduce the interference while providing the high data rate using the high-rate MCS.

Table 6.13: Results for the seventh topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	Total
max,max,max	42.709	10.3	9.35	5.63	11.12	6.86	9.34	52.6
min,max,max	55.023	11.33	10.47	6.16	11.89	6.91	9.59	56.35
min,max,min	68.015	11.21	10.38	8.55	12.93	6.57	9.89	59.53
min,min,min	**118.317**	**12.45**	**11.76**	**9.41**	**13.88**	**7.15**	**10.78**	**65.43**

6.4.3.8 Eighth Topology

Table 6.14 illustrates the results for the eighth topology. From the seventh topology, *H1-2* is moved to D308 while *AP1* and *H1-1* are still in D307. In this topology, the best transmission power for *AP1* becomes the maximum one because there is a host in a different room. The maximum power is necessary to avoid the throughput drop caused by the signal attenuation at the wall.

Table 6.14: Results for the eighth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	Total
max,max,max	37.967	10.6	3.38	5.52	11.08	6.68	8.22	45.38
max,max,min	56.723	11.9	4.6	7.58	12.65	6.73	8.11	51.57
max,min,min	**64.268**	**12.85**	**5.71**	**7.65**	**12.37**	**9.97**	**11.36**	**59.91**
min,min,min	52.713	10.93	3.88	5.9	11.61	6.76	9.65	48.73

6.4.3.9 Ninth Topology

Table 6.15 demonstrates the results for the ninth topology. From the seventh topology, *H2-2* is moved to the front of D306. The best transmission power for *AP2* becomes the maximum one because there is a host which is far from it. The maximum power provides enough signal for the host which is far.

Table 6.15: Results for the ninth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	Total
max,max,max	27.737	9.44	6.31	9.12	3.64	6.53	7.21	42.25
min,max,max	32.947	9.64	6.37	11.43	3.15	8.89	10.38	49.86
min,max,min	**52.956**	**11.65**	**7.51**	**12.15**	**4.11**	**11.1**	**12.77**	**59.29**
min,min,min	24.027	10.31	7.54	10.42	3.13	7.87	8.27	47.54

6.4.3.10 Tenth Topology

In the tenth topology, from the ninth topology, *H3-2* is moved to D306. Table 6.16 shows the results for this topology. The best transmission power for *AP3* becomes the maximum one because there is a host which is far from it. The maximum power gives sufficient signal for the host which is far.

Table 6.16: Results for the tenth topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	Total
max,max,max	20.166	12.47	6.56	8.83	3.64	6.42	1.24	39.16
min,max,max	**25.238**	**12.95**	**6.79**	**11.55**	**4.63**	**10.53**	**2.53**	**48.98**
min,min,max	15.303	12.1	6.13	8.61	1.27	7.55	1.19	36.85
min,min,min	4.018	10.9	6.59	8.41	1.53	5.63	0.32	33.38

6.4.3.11 Eleventh Topology

In the eleventh topology, *H1-2* is moved to D306, *H2-2* is moved to the front of D308 and *H3-2* is moved to the front of D306, from the seventh topology. Table 6.17 reveals the results for this topology. The best transmission power for each AP is the maximum one because there are hosts which are in a far position and placed in a different room from the associated AP. The maximum power is necessary to avoid the throughput drop caused by the distance loss of signal and the signal attenuation by the wall.

Table 6.17: Results for the eleventh topology with three APs.

P_{AP1},P_{AP2},P_{AP3}	average SINR	throughput (Mbps)						
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	Total
max,max,max	**16.333**	**12.31**	**1.98**	**10.41**	**1.53**	**8.54**	**1.8**	**36.57**
max,max,min	12.68	12.05	2.43	10.04	2.11	5.63	0.23	32.49
max,min,min	2.534	12.86	2.71	6.74	0.25	5.44	0.31	28.31
min,min,min	1.323	10.52	0.43	7.63	0.41	6.62	0.34	25.95

6.4.4 Results for Four-AP Case

This section shows the results for the four-AP case. Four APs are placed in different rooms. The four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to the APs. Based on the results, the method always selects the best transmission power for each AP.

6.4.4.1 First Topology

In the first topology, *AP1* and *H1* are closely located in D307. *AP2* and *H2* are located in front of D308. *AP3* and *H3* are located in front of D302. *AP4* and *H4* are located in the Refresh corner. Table 6.18 shows the results for the first topology. The best transmission power is the minimum one for any AP because the associated host is near.

Table 6.18: Results for the first topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average SINR	throughput (Mbps)				
		AP1,H1	AP2,H2	AP3,H3	AP4,H4	Total
max,max,max,max	15.81	20.1	14.63	18.4	12.93	66.06
min,max,max,max	25.91	20.25	15.72	19.81	14.55	70.33
min,min,max,max	30.078	21.14	16.32	20.77	15.74	73.97
min,min,min,max	62.704	21.54	17.51	21.41	15.5	75.96
min,min,min,min	**94.215**	**21.76**	**18.44**	**21.98**	**15.17**	**77.35**

6.4.4.2 Second Topology

Table 6.19 shows the results for the second topology. From the first topology, *H1* is moved to D308. The best transmission power for *AP1* becomes the maximum one because the host is located in a different room.

Table 6.19: Results for the second topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average SINR	throughput (Mbps)				
		AP1,H1	AP2,H2	AP3,H3	AP4,H4	Total
max,max,max,max	11.078	6.58	14.43	18.51	12.65	52.17
max,min,max,max	15.362	7.74	14.22	19.37	14.75	56.08
max,min,min,max	21.776	7.85	16.31	19.93	15.97	60.06
max,min,min,min	**41.398**	**7.99**	**16.78**	**20.19**	**17.78**	**62.74**
min,min,min,min	9.362	1.28	15.65	18.48	13.56	48.97

6.4.4.3 Third Topology

The results for the third topology are shown in Table 6.20. From the second topology, *H2* is moved to the front of D306. The best transmission power for *AP2* also becomes the maximum one because the host is relatively far from it.

Table 6.20: Results for the third topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average SINR	throughput (Mbps)				
		AP1,H1	AP2,H2	AP3,H3	AP4,H4	Total
max,max,max,max	9.819	6.43	9.95	18.13	13.74	48.25
max,max,min,max	12.491	7.76	11.87	19.01	14.83	53.47
max,max,min,min	**20.893**	**8.55**	**13.76**	**20.13**	**18.21**	**60.65**
max,min,min,min	8.339	6.65	6.12	20.03	14.89	47.69
min,min,min,min	1.884	2.54	6.04	20.31	16.08	44.97

6.4.4.4 Fourth Topology

In the fourth topology, *H3* is moved to D306 from the third topology. Table 6.21 demonstrates the results for the fourth topology. The best transmission power for *AP3* also becomes the maximum one because the host is far from it.

Table 6.21: Results for the fourth topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average SINR	throughput (Mbps)				
		AP1,H1	AP2,H2	AP3,H3	AP4,H4	Total
max,max,max,max	8.884	6.76	7.53	5.75	11.53	31.57
max,max,max,min	**10.064**	**7.82**	**8.41**	**7.77**	**13.7**	**37.7**
max,min,max,min	7.893	6.31	6.12	5.06	12.15	29.64
min,min,max,max	2.492	5.98	6.01	5.32	11.67	28.98
min,min,min,min	1.209	5.46	6.14	5.11	7.79	24.5

6.4.4.5 Fifth Topology

In the fifth topology, each AP is associated with two hosts. Each AP and its associated hosts are close. Table 6.22 reveals the results for this topology. The best transmission power for any AP is the minimum one because any host is near the associated AP.

Table 6.22: Results for the fifth topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average SINR	throughput (Mbps)								
		AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	AP4,H4-1	AP4,H4-2	Total
max,max,max,max	5.114	7.12	6.43	5.99	4.31	7.33	6.87	6.39	9.05	53.49
max,min,max,max	11.339	7.98	7.01	5.54	4.1	7.53	7.17	7.65	10.01	56.99
max,min,max,min	13.03	8.55	7.74	6.01	4.93	8.53	7.77	8.91	8.01	60.45
min,min,max,min	16.329	8.42	7.54	6.83	7.43	7.98	8.54	8.43	7.29	62.46
min,min,min,min	**42.256**	**9.41**	**7.64**	**8.53**	**7.36**	**9.03**	**7.53**	**8.81**	**9.4**	**67.71**

6.4.4.6 Sixth Topology

In the sixth topology, *H1-2* is moved to D308, *H2-2* and *H4-2* are moved to in front of D306, and *H3-2* is moved to D306, from the fifth topology. Table 6.23 illustrates the results for this topology. The best transmission power for any AP becomes the maximum one where at least one associated host is located in a different room or far from the AP.

Table 6.23: Results for the sixth topology with four APs.

P_{AP1},P_{AP2},P_{AP3},P_{AP4}	average	throughput (Mbps)								
	SINR	AP1,H1-1	AP1,H1-2	AP2,H2-1	AP2,H2-2	AP3,H3-1	AP3,H3-2	AP4,H4-1	AP4,H4-2	Total
max,max,max,max	**0.258**	**3.12**	**0.51**	**2.72**	**0.56**	**2.54**	**0.81**	**2.65**	**0.34**	**13.25**
max,min,max,max	0.219	2.71	0.35	2.49	0.47	1.92	0.74	2.47	0.8	11.95
max,min,max,min	0.208	2.68	0.49	2.58	0.54	1.85	0.68	1.54	0.29	10.65
min,min,max,min	0.117	2.25	0.31	2.76	0.43	1.45	0.41	1.44	0.56	9.61
min,min,min,min	0.024	2.14	0.19	2.33	0.01	1.31	0.1	1.34	0.42	7.84

6.4.5 Summary of Results

There are several topologies that have been evaluated to confirm the effectiveness of the proposal. All topologies represent the different numbers and locations of APs and hosts.

Based on the results, the proposal always selects the best transmission power for each AP. When the distance between AP and host is near, AP should be assigned to minimum power. Even though the received signal in the near host is reduced because of the minimum power, the throughput remains similar. Thus, minimum power can reduce the interference, so that the total throughput is improved. For the far location of the host or host which is in the different room from the associated AP, the AP should be assigned to maximum power to avoid the throughput drop caused by the distance loss of signal or the signal attenuation by the wall.

6.5 Comparison Evaluations

This section presents the comparison evaluations of the proposed method with other methods. The same experiment setup in Section 6.4.1 is adopted in these evaluations. Here, the following three methods are considered:

1. The first method assigns the different POCs with the same maximum channel interval and the maximum transmission power to the APs.

2. The second method assigns the different POCs with the same maximum channel interval to the APs and optimizes the transmission power by the proposal.

3. The third method optimizes the channel assignment by the proposal and assigns the maximum transmission power to the APs.

6.5.1 Evaluation Scenarios

The proposed method is evaluated under various scenarios for different network conditions. Here, the different conditions are considered in the following terms:

(1) the building,

(2) the number of APs and hosts,

(3) the located rooms of APs, and

(4) the distances between APs and hosts.

For (1), two buildings in Okayama University, *Engineering Building #2* and *Graduate School Building*, are used for the network field. The results in *Engineering Building #2* are presented and discussed in Section 6.5.2. The results in *Graduate School Building* are presented and discussed in Section 6.5.3.

For (2), *two*, *three*, and *four* are investigated for the number of APs and hosts in the network. The network with *two* APs/hosts are investigated in *Case 1* - *Case 3* in both buildings. The network with *three* APs/hosts are investigated in *Case 4* - *Case 7* in both buildings. The network with *four* APs/hosts are investigated in *Case 8* - *Case 12* in both buildings.

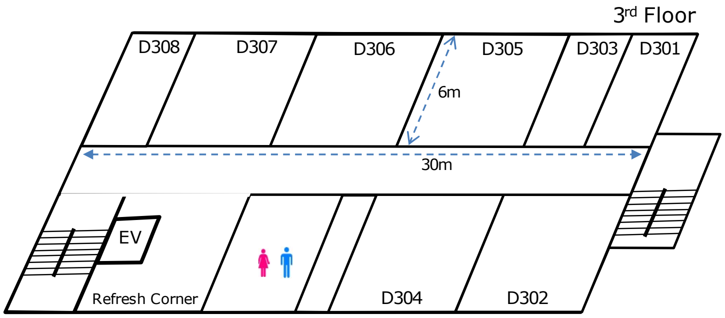
For (3), the strongly interfered condition where all the APs are located in the same room, the medium interfered condition where a subset of the APs are located in the same room, and the less interfered condition where all the APs are located in different rooms, are considered. The strongly interfered condition is considered in *Case 1*, *Case 4*, and *Case 8*. The medium interfered condition is considered in *Case 5*, *Case 9*, and *Case 10*. The less interfered condition is considered in *Case 2*, *Case 3*, *Case 6*, *Case 7*, *Case 11*, and *Case 12*.

For (4), the strong receiving signal condition where the AP and the host are located in the same room with 1*m* distance, and the weak receiving signal condition where the AP and the host are located in different rooms with 8*m* distance, are considered. The strong receiving signal condition is considered in *Case 1*, *Case 2*, *Case 4*, *Case 5*, *Case 6*, *Case 8*, *Case 9*, *Case 10*, and *Case 11*. The weak receiving signal condition is considered in *Case 3*, *Case 7*, and *Case 12*. These three cases are considered natural, even if the hosts can be located in different rooms from the APs, because the APs are located in different rooms. In other cases, some APs are located in the same room. Thus, the hosts should be located in the same rooms as the APs.

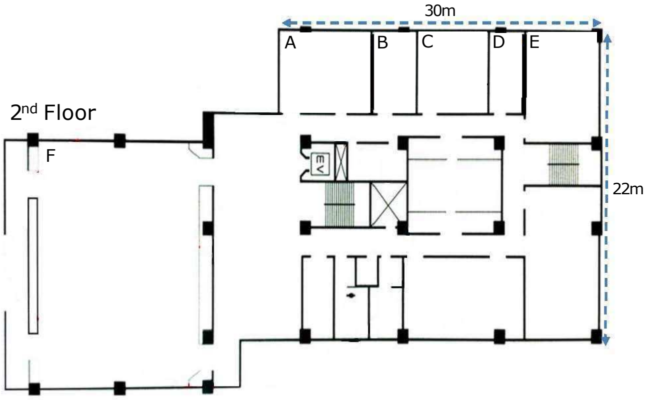
Figure 6.3 illustrates the fields in this evaluation. Table 6.24 and 6.25 display experiment cases in Engineering Building #2 and Graduate School Building, respectively.

Table 6.24: Experiment cases in Engineering Building #2.

Case	Number of APs	Scenario	AP1 Location	H1 Location	AP2 Location	H2 Location	AP3 Location	H3 Location	AP4 Location	H4 Location
1	2	All APs are in one room	D307	D307	D307	D307	-	-	-	-
2	2	All APs are in different room	D307	D307	D306	D306	-	-	-	-
3	2	All APs are in different room	D307	D306	In front of D301	In front of D303	-	-	-	-
4	3	All APs are in one room	D307	D307	D307	D307	D307	D307	-	-
5	3	Two APs are in one room	D307	D307	D307	D307	D306	D306	-	-
6	3	All APs are in different rooms	D308	D308	D307	D307	D306	D306	-	-
7	3	All APs are in different rooms	D307	D306	In front of D308	In front of D308	In front of D301	In front of D306	-	-
8	4	All APs are in one room	D306	D306	D306	D306	D306	D306	D306	D306
9	4	Three APs are in one room	D306	D306	D306	D306	D306	D306	D307	D307
10	4	Two APs are in one room	D306	D306	D306	D306	D307	D307	D307	D307
11	4	All APs are in different rooms	D308	D308	D307	D307	D306	D306	In front of D301	In front of D301
12	4	All APs are in different rooms	D307	D308	In front of D308	In front of D306	In front of D301	D306	Refresh Corner	Refresh Corner



Engineering Building #2



Graduate School Building

Figure 6.3: Experiment fields.

Table 6.25: Experiment cases in Graduate School Building.

Case	Number of APs	Scenario	AP1 Location	H1 Location	AP2 Location	H2 Location	AP3 Location	H3 Location	AP4 Location	H4 Location
1	2	All APs are in one room	A	A	A	B	-	-	-	-
2	2	All APs are in different room	A	A	C	C	-	-	-	-
3	2	All APs are in different room	A	B	C	D	-	-	-	-
4	3	All APs are in one room	F	F	F	F	F	F	-	-
5	3	Two APs are in one room	A	A	A	A	C	C	-	-
6	3	All APs are in different rooms	A	A	C	C	E	E	-	-
7	3	All APs are in different rooms	A	B	C	D	E	In front of D	-	-
8	4	All APs are in one room	F	F	F	F	F	F	F	F
9	4	Three APs are in one room	F	F	F	F	F	F	In front F	In front A
10	4	Two APs are in one room	A	A	A	B	C	C	C	D
11	4	All APs are in different rooms	A	A	C	C	E	E	In front of F	In front of F
12	4	All APs are in different rooms	A	B	C	D	E	In front of D	In front of F	In front of F

6.5.2 Evaluation Results in Engineering Building #2

Figure 6.4 demonstrates the experiment results in Engineering Building #2. It indicates that the proposal always selects the best channel and transmission power for every AP that gives the higher throughput than any comparison method. For references, Table 6.26 reveals the RSS between APs and Table 6.27 shows the assigned channel and transmission power to each AP by the proposal.

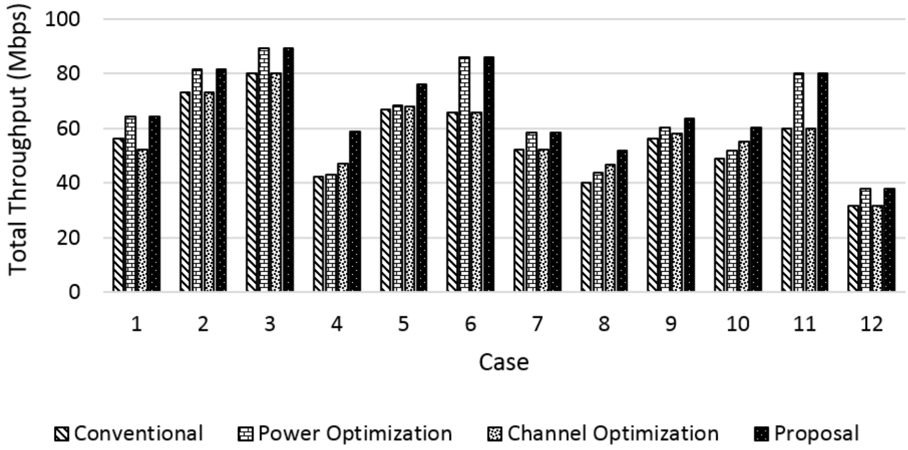


Figure 6.4: Results in Engineering Building #2.

Table 6.26: Measured RSS between APs in Engineering Building #2.

Case	$RSS_{AP1,AP2}$ (dBm)	$RSS_{AP1,AP3}$ (dBm)	$RSS_{AP2,AP3}$ (dBm)	$RSS_{AP1,AP4}$ (dBm)	$RSS_{AP2,AP4}$ (dBm)	$RSS_{AP3,AP4}$ (dBm)
1	-33.18	-	-	-	-	-
2	-55.01	-	-	-	-	-
3	-79.02	-	-	-	-	-
4	-30.93	-39.06	-31.13	-	-	-
5	-30.86	-59.57	-54.48	-	-	-
6	-61.87	-79.68	-62.36	-	-	-
7	-62.98	-79.37	-74.55	-	-	-
8	-33.08	-33.24	-39.27	-38.96	-32.89	-33.19
9	-33.06	-33.31	-39.41	-56.32	-54.83	-53.43
10	-33.11	-53.74	-55.67	-56.13	-54.71	-33.34
11	-61.86	-79.64	-62.34	-89.87	-83.13	-72.34
12	-62.77	-79.37	-74.23	-74.64	-61.05	-76.51

Table 6.27: Channel and transmission power assignment results in Engineering Building #2.

Case	Optimized channel				Optimized transmission power			
	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
1	1+5	9+13	-	-	min.	min.	-	-
2	1+5	9+13	-	-	min.	min.	-	-
3	1+5	9+13	-	-	max.	min.	-	-
4	1+5	1+5	9+13	-	min.	min.	min.	-
5	1+5	1+5	9+13	-	min.	min.	min.	-
6	5+9	1+5	9+13	-	min.	min.	min.	-
7	5+9	1+5	9+13	-	max.	min.	max.	-
8	1+5	1+5	1+5	9+13	min.	min.	min.	min.
9	1+5	1+5	1+5	9+13	min.	min.	min.	min.
10	1+5	1+5	9+13	9+13	min.	min.	min.	min.
11	1+5	9+13	4+8	7+11	min.	min.	min.	min.
12	1+5	9+13	4+8	7+11	max.	max.	max.	min.

6.5.2.1 Case 1

Two APs and two hosts are in the same room that has $7m \times 6m$ size. Thus, two different OCs are assigned to the APs. Besides, the minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.2.2 Case 2

Two APs are placed in different rooms. Two different OCs are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.2.3 Case 3

Two APs are located in far places. Two different OCs are assigned to them. The maximum transmission power is assigned to *AP1* since *H1* is far from it. The minimum power is assigned to *AP2* since *H2* is near it.

6.5.2.4 Case 4

Three APs and three hosts are located in the same room. The same OC is assigned to *AP1* and *AP2* because the RSS between them is $-30.93dBm$ that is larger than the threshold $-60dBm$. Another OC is assigned to *AP3* to reduce the interferences from the other APs. Then, the minimum transmission power is assigned to every AP since any host is located near the AP.

6.5.2.5 Case 5

Two APs are positioned in the same room, and another AP is in a different room. Thus, the same OC is assigned to *AP1* and *AP2*, and another OC is assigned to *AP3*. The minimum transmission power is assigned to every AP since any host is located near the AP.

6.5.2.6 Case 6

Three APs are put in the different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.2.7 Case 7

Three APs are located in the different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1* and *AP3* since the associated host is far from the AP. The minimum power is assigned to *AP2* since the associated host is near it.

6.5.2.8 Case 8

Four APs and four hosts are placed in the same room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4* to reduce the interferences from the other APs. The minimum transmission power is assigned to every AP since any host is near the AP.

6.5.2.9 Case 9

Three APs are located in the same room and another AP is in a different room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4*. The minimum transmission power is assigned to each AP since any host is near the AP.

6.5.2.10 Case 10

Two APs are positioned in the same room. The same OC is assigned to *AP1* and *AP2*. Another OC is assigned to *AP3* and *AP4*. The minimum transmission power is assigned to each AP because any host is near the AP.

6.5.2.11 Case 11

Four APs are put in the different rooms. The RSS between them is smaller than the threshold. Thus, the four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.2.12 Case 12

Four APs are located in the different rooms. The RSS between them is smaller than the threshold. The four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1*, *AP2*, and *AP3*, since the associated host is far from the AP. The minimum power is assigned to *AP4* since the associated host is near it.

6.5.3 Evaluation Results in Graduate School Building

Figure 6.5 demonstrates the experiment results in Graduate School Building. Again, the proposal gives the highest throughput for any case. Table 6.28 reveals the RSS between the APs, and Table 6.29 shows the assigned channel and transmission power to each AP by the proposal.

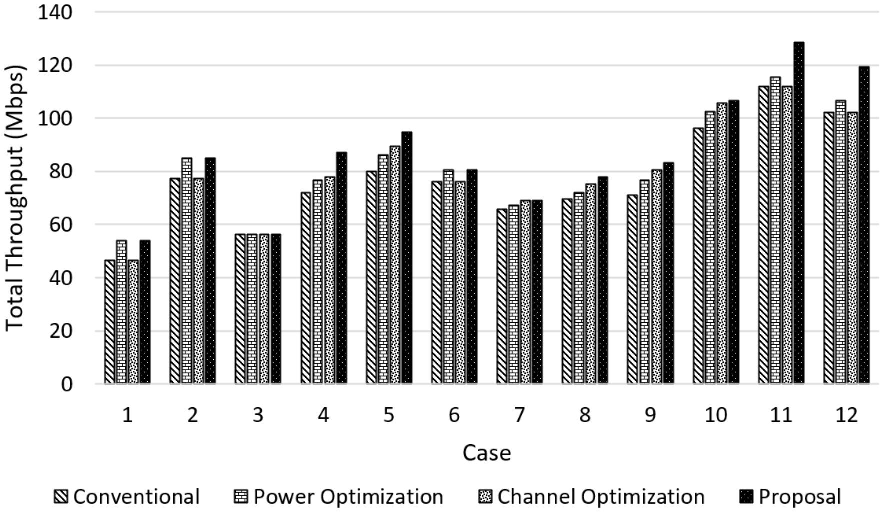


Figure 6.5: Results in Graduate School Building.

Table 6.28: Measured RSS between APs in Graduate School Building.

Case	$RSS_{AP1,AP2}$ (dBm)	$RSS_{AP1,AP3}$ (dBm)	$RSS_{AP2,AP3}$ (dBm)	$RSS_{AP1,AP4}$ (dBm)	$RSS_{AP2,AP4}$ (dBm)	$RSS_{AP3,AP4}$ (dBm)
1	-33.56	-	-	-	-	-
2	-74.54	-	-	-	-	-
3	-74.54	-	-	-	-	-
4	-46.18	-52.11	-46.23	-	-	-
5	-46.34	-79.31	-70.42	-	-	-
6	-74.16	-79.44	-76.21	-	-	-
7	-74.16	-79.44	-76.21	-	-	-
8	-44.16	-43.73	-50.39	-50.81	-43.92	-44.45
9	-44.11	-43.69	-50.42	-69.61	-68.38	-66.75
10	-35.24	-56.52	-57.21	-58.98	-56.53	-35.81
11	-74.77	-79.65	-76.33	-64.59	-78.12	-89.73
12	-74.77	-79.65	-76.33	-64.59	-78.12	-89.73

Table 6.29: Channel and transmission power assignment results in Graduate School Building.

Case	Optimized channel				Optimized transmission power			
	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
1	1+5	9+13	-	-	min.	max.	-	-
2	1+5	9+13	-	-	max.	max.	-	-
3	1+5	9+13	-	-	max.	max.	-	-
4	1+5	1+5	9+13	-	min.	min.	min.	-
5	1+5	1+5	9+13	-	min.	min.	min.	-
6	5+9	1+5	9+13	-	min.	min.	min.	-
7	5+9	1+5	9+13	-	max.	max.	max.	-
8	1+5	1+5	1+5	9+13	min.	min.	min.	min.
9	1+5	1+5	1+5	9+13	min.	min.	min.	max.
10	1+5	1+5	9+13	9+13	min.	max.	min.	max.
11	1+5	4+8	7+11	9+13	min.	min.	min.	min.
12	1+5	4+8	7+11	9+13	max.	max.	max.	min.

6.5.3.1 Case 1

Two APs are positioned in the same room. Two different OCs are assigned to them. The minimum transmission power is assigned to *AP1* because *H1* is near it. The maximum power is assigned to *AP2* since *H2* is in a different room.

6.5.3.2 Case 2

Two APs are placed in different rooms. Two different OCs are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.3.3 Case 3

Two APs are located in different rooms. Two different OCs are assigned to them. The maximum transmission power is assigned to *AP1* and *AP2* since any host is located in a different room.

6.5.3.4 Case 4

Three APs and three hosts are placed in a big room. The same OC is assigned to *AP1* and *AP2* because the RSS between them is larger than the threshold $-60dBm$. Another OC is assigned to *AP3*. Then, the minimum transmission power is assigned to each AP since any host is near the AP.

6.5.3.5 Case 5

Two APs are located in the same room and another AP is in a different room. The same OC is assigned to *AP1* and *AP2*, and another OC is assigned to *AP3*. The minimum transmission power is assigned to each AP because any host is near the AP.

6.5.3.6 Case 6

Three APs are positioned in the different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel*

9+13, are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.3.7 Case 7

Three APs are put in the different rooms. The RSS between them is smaller than the threshold. Thus, the three POCs with the same channel distance, *channel 1+5*, *channel 5+9*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to each AP since any associated host is located in a different room from the AP.

6.5.3.8 Case 8

Four APs and four hosts are placed in the same room. The same OC is assigned to *AP1*, *AP2*, and *AP3*, another OC is assigned to *AP4*. The minimum transmission power is assigned to every AP since any host is near the AP.

6.5.3.9 Case 9

Three APs are positioned in the same room and another AP is in a different room. The same OC is assigned to *AP1*, *AP2*, and *AP3*. Another OC is assigned to *AP4*. The minimum transmission power is assigned to *AP1*, *AP2*, and *AP3*, since the associated host is near the AP. The maximum power is assigned to *AP4* since the associated host is far from it.

6.5.3.10 Case 10

Two APs are located in the same room. The same OC is assigned to *AP1* and *AP2*, another OC is assigned to *AP3* and *AP4*. The minimum transmission power is assigned to *AP1* and *AP3* because their associated hosts are in a near position. The maximum power is assigned to *AP2* and *AP4* because their associated hosts are in a different room.

6.5.3.11 Case 11

Four APs are placed in different rooms. The RSS between them is smaller than the threshold. Thus, the four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The minimum transmission power is assigned to each AP since the host is located near the AP.

6.5.3.12 Case 12

Four APs are put in different rooms. The RSS between them is smaller than the threshold. The four POCs with the same channel distance, *channel 1+5*, *channel 4+8*, *channel 7+11*, and *channel 9+13*, are assigned to them. The maximum transmission power is assigned to *AP1*, *AP2*, and *AP3* since the associated host is far from the AP. The minimum power is assigned to *AP4* since the associated host is near it.

6.6 Summary

This chapter presented the *transmission power optimization method* with the channel assignment consideration for any number of APs in WLAN. The results confirmed the effectiveness of this method. The next chapter will introduce the related works of this study.

Chapter 7

Related Works in Literature

This chapter reviews related works to this study. Several works have discussed the transmission power optimization of the access point. However, most of them verified the effectiveness of their proposals only in simulations. On the other hand, the effectiveness of the proposal in this thesis was verified through real testbed experiments.

In [88][89], Qiao et al. proposed an optimal low-energy transmission strategy called *MiSer*, which can be deployed in the format of *RTS-CTS-Data-Ack*. The key idea is to combine the transmission power control (TPC) and the physical layer (PHY) rate adaptation, and to compute offline the optimal rate-power combination table, where at runtime, a wireless station determines the most energy-efficient transmission strategy for each data frame transmission by a simple table lookup. However, the effectiveness was verified only in simulations.

In [90], Mhatre et al. established sufficient conditions for starvation-free power control, and proposed an algorithm for the joint optimization of the transmit power and clear channel assessment (CCA) threshold, both for centralized and distributed implementation. It will apply the higher transmit power to the cells with higher number of clients, or clients with a poor quality channel, where the product of the CCA threshold and the transmit power for all the APs be constant. If the transmit power of a node is high, the CCA threshold should turn out to be low, which means that if you want to shout, you need to listen more carefully so as not to disturb those who are whispering. Using OPNET simulations, they demonstrated that the proposal can result in up to 290% improvement in throughputs.

In [91], Zhang et al. proposed a heuristic algorithm to reduce the total cost of AP placement by gradually merging neighboring APs. They consider the placement of APs with multi-radio and multi-power-level in an indoor environment, propose the metric *Client to Interference Ratio (CIR)* to select the merging of APs, and introduce the signal-based Delaunay graph to ensure the merging only between two neighboring APs. Still, the effectiveness was merely verified in simulations.

In [92], Gandarillas et al. presented an AP transmission power minimization method to minimize the overall co-channel and adjacent channel interferences and expand the coverage range of the WLAN, which controls the power based on the *modulation coding scheme (MCS)* rate, the percentage of packet transmission retries, and the calculated data communication channel occupancy. Nevertheless, its implementation appears to be challenging because it will acquire the MCS rate. Besides, the values of several parameters should be properly selected for each WLAN, where they can be different depending on the adopted devices, protocols, and channel environments. The effectiveness was verified both in simulations and testbed experiments. However, in the experiment results, the throughput and the percentage of packet transmission retries were not improved when the power was reduced, although they claimed that reducing the transmit-power of one of the APs improves the quality of service of the links involving the neighboring APs.

In [93], Choi et al. introduced a random-access medium access control protocol using distributed power control to manage inter-client interference in WLAN with full-duplex capable APs with half-duplex clients, called *PoCMAC*. The optimal transmit power is found by solving the linear programming problem to maximize the SINRs of the uplink and downlink transmissions. The effectiveness of the proposal was verified both in simulations using MATLAB and testbed experiments using *Wireless Open Access Research Platform*. Nonetheless, in testbed experiments, they only showed the changes in the received powers by the proposal, where they did not show throughput improvements.

In [94], Roslan et al. proposed a control scheme of tuning the transmission power and carrier sense threshold of a host to enhance network throughput and ensure fairness among the hosts in dense IEEE 802.11 WLAN by solving the hidden and exposed terminal problems. It adopts Bloom filter to distinguish associated hosts within the same basic service set (BSS) from the others while reducing the overhead. When a host is hidden or could not be heard by other neighboring hosts, the transmission power can be increased, and when an exposed host is detected, the power is reduced. The effectiveness was verified only in simulations using *Scenargie*.

In [95], Guessous et al. presented a transmission power control method to maximize transmission opportunities for hosts by considering beamforming for extremely lessened co-channel interferences. It assumes that the AP must support MIMO technologies and can estimate DOA and beamforming directions while a client may support omnidirectional transmissions with lowered power level. The effectiveness was verified only in simulations using MATLAB.

In [96], Tewari et al. introduced a combined transmission power and partially overlapping channels (POCs) assignment optimization to maximize the network performance in dense WLAN. Considering multiple overlapping transmissions cause a significant performance degradation due to high interference from the limited non-overlapping channels. The effectiveness was confirmed only in simulations regardless.

In [97], Shitara et al. proposed an AP transmission power control method using an indicator issued from a neighbor AP. If the AP knows that the channel occupancy rate (COR) of the overlapping basic service set (OBSS) is increasing by reported from associated hosts, it issues the indicator to let other APs hearing it change their transmission powers accordingly. However, the effectiveness was verified only in simulations.

In [98], Garcia et al. presented a heuristic algorithm composed of four phases to improve the network average data rate by finding the optimal channel and transmission power allocation to each AP from all the available channels and the power levels. They assumed that the *spectrum overlapping factor* is given for each channel distance or spacing between the two channels to estimate the interference between two signals, and the *signal-to-interference noise ratio (SINR)* can be calculated using this factor with the received signal powers from the APs and the received interference plus noise power. Then, the data rate or throughput is uniquely given for each SINR. These assumptions may not be correct. For example, for *Case 4* in Section 6.5 where three APs are located in the same room, it will give the higher throughput if the different POCs with the same maximum channel interval are assigned to them, which will give smaller interferences with smaller spectrum overlapping factors by the assumptions. However, as shown in Figures 6.4 and 6.5, the results of assigning the same POC to the two APs actually gives higher throughputs. Besides, they verified the effectiveness of their proposal in simulations using MATLAB, not in experiments using real network devices.

In [99], Zhao et al. proposed the joint transmit power control and channel allocation optimization to reduce interference and improve the throughput. First, they analyzed the correlation between transmit power and channel, and formulated the interference optimization as a *mixed integer nonlinear programming (MINLP)* problem. They used *reinforcement learning (RL)* to optimize power and channel allocation and obtained the optimal joint optimization strategy through off-line training to reduce the computational complexity. And they also use the event-driven mechanism of Q-learning to decrease the complexity of online learning. However, the effectiveness was verified only in simulations.

Chapter 8

Conclusion

This thesis presented the study of the *transmission power optimization method* with the channel assignment consideration for multiple *access-points* concurrent communications in *wireless local-area networks (WLAN)*.

First, I surveyed the *IEEE 802.11* wireless network technologies related to this thesis, including the overview of IEEE 802.11 WLAN, IEEE 802.11n protocols, features of IEEE802.11n protocol, Linux tools for wireless networking, and the software AP using a *Raspberry Pi* device.

Second, I reviewed our previous studies related to this thesis, including the *elastic WLAN system* and testbed implementation using *Raspberry Pi* APs.

Third, I presented experimental observations of the throughput performance with different transmission power. I described the experiment setup to conduct measurements and showed the throughput results. *Channel bonding (CB)* at $2.4GHz$ was used in the AP to enhance the link capacity.

Fourth, I proposed the *transmission power optimization method* for two concurrently communicating APs in the elastic WLAN system. It selects either the maximum or minimum power for each AP such that *signal-to-noise ratio (SNR)* is the highest.

Fifth, I generalized the *transmission power optimization* with channel assignment consideration for concurrently communicating multiple APs in WLAN. To simplify the optimization procedure and decrease the execution cost, the channels of APs are optimized before the transmission power optimization.

Finally, I implemented the proposed method for performance evaluations on the *elastic WLAN system testbed*, using up to four *Raspberry Pi APs*. I conducted extensive experiments in two buildings at Okayama University. The results confirmed the effectiveness of the proposal.

In future studies, I will further enhance the *transmission power optimization method* with the channel assignment consideration by assigning CB and non-CB. Then, I will continue to evaluate the proposals in various network fields.

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