A Study of Active Access-Point Selection Algorithm for Wireless Mesh Network under Practical Conditions

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Abstract

As an inexpensive, scalable, and flexible Internet-access network, a *wireless Internet-access mesh network (WIMNET)* is composed of multiple *access-points (APs)* that are connected by wireless links. WIMNET can improve the dependability to link or AP failures by allocating APs redundantly in the network field. Because the redundant APs may increase the operational cost and degrade the performance due to increasing radio interferences, only the necessary APs for communications between the hosts and the Internet gateway should be activated in conventional situations.

Previously, we have proposed an *active AP selection algorithm* to select the minimum number of APs to be activated for WIMNET that has a single Internet *gateway (GW)*, such that the overall throughput is maximized, under the assumption that every link has the same constant speed. However, our preliminary experiments for the emerging high-speed *IEEE802.11n* protocol that should be introduced into WIMNET found that this speed is greatly affected by the link environment such as the distance. Besides, in practical implementations of large-scale WIMNET, multiple GWs are usually necessary to increase the capacity of Internet connections, and the number of hops between a GW and a host should be limited. Furthermore, the minimum throughput should be provided to a host as QoS (Quality of Service) when it is exclusively connected with the GW.

In this thesis, we first present the extension of the active AP selection algorithm to select active APs under practical conditions of link speed changes, multiple GWs, the hop count limitation, and QoS constraints. We also extend the *routing algorithm* used in the active AP selection algorithm procedure and the *WIMNET simulator* for throughput evaluations. We verify the effectiveness of the extended active AP selection algorithm through extensive simulations using the extended WIMNET simulator.

Then, we present link speed measurement results when *Transmission Control Protocol (TCP)* is adopted with IEEE 802.11ac devices from three vendors. In our measurements, we adopt different conditions for network fields such as AP locations, link distances, one or two-hop communications, wall existences, and repeater existences. Then, the experimental results show that TCP throughputs are greatly affected by vendors, communication conditions and physical conditions.

In future studies, we will study the proper assignment of the minimum link speed parameter that is critical for the active AP minimization and the overall throughput maximization, the proper handling of dynamic traffic changes, the further algorithm extension to different hop limitations, and the system implementation for real networks.

Acknowledgements

List of Publications

Journal Paper

1. **Chang Choon Chew**, Nobuo Funabiki, Wataru Maruyama, and Sho Fujita, "An extended active access-point selection algorithm for link speed changes in wireless mesh networks," Int. J. Space-Based and Situated Computing, vol. 4, Nos. 3/4, pp. 184-193, November 2014.

International Conference Paper

2. **Chang Choon Chew**, Nobuo Funabiki, and Sho Fujita, "Extensions of active access-point selection algorithm for wireless mesh networks using IEEE802.11ac protocol," The Second International Symposium on Computing and Networking (CANDAR, PDAA), pp. 310-314, December 2014.

Other Papers

3. **Chang Choon Chew**, Nobuo Funabiki, Toru Nakanishi, and Kan Watanabe, "Throughput measurements using IEEE802.11n and 11ac devices for high-speed wireless networks," The 2013 (64th) Chugoku-branch Joint Convention of Institutes of Electrical and Information Engineers, pp. 232-233, October 2013.

4. **Chang Choon Chew**, Nobuo Funabiki, Toru Nakanishi, and Kan Watanabe, "Throughput measurements using IEEE 802.11ac devices for high-speed wireless networks," IEICE Technical Report, vol. 113, no. 463, CAS2013-94, pp. 23-28, March 2014.

5. **Chang Choon Chew** and Nobuo Funabiki, "Throughput measurements in big room with different access point locations for IEEE 802.11ac wireless networks," IEICE Society Conference 2014, pp. S-38-39, September 2014.

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Chapter 1

Introduction

1.1 Backgrounds

Nowadays, as an inexpensive and flexible Internet-access network, a *wireless local area network (WLAN)* has been deployed all over the world [1]. Because a WLAN does not need a wired cable to connect a host with a network AP, it has several advantages over a wired network such as lower installation and management costs, easy host relocations, and flexible service areas. An AP acts as a connection hub to a wired network in a WLAN. As a result, WLANs have been installed in a lot of places and organizations, including governments, companies, homes, and schools. WLAN services have been offered even in moving public spaces such as buses, trains and airplanes.

In a WLAN, one AP can provide a limited communication range within approximately $100m$ distance from it even in an open space due to the weak transmission signal. For a WLAN service to a wider area, multiple APs should be allocated there. These APs are usually connected by cables. However, the cabling cost may impair the advantage of a WLAN. Besides, cables may not be able to be laid down in places such as outdoors and old buildings.

One solution to this problem is a mesh allocation of multiple APs that are connected through wireless links between adjacent APs, in addition to conventional wireless connections between APs and hosts. Every APs in the field can be communicated through multi-hop fashions, where intermediate APs act as repeaters to relay packets. This multi-hop WLAN is called a *wireless mesh network (WMN)* [2–9].

Among the variants of wireless mesh networks understudies, we have focused on a simple architecture that uses only APs as wireless mesh routers, and realizes wireless communications between APs mainly on the MAC layer using the *wireless distribution system (WDS)* [1]. At least one AP acts as a GW to the Internet, and any host can connect to the Internet through this GW. Any host is first associated with its adjacent AP, and then, reaches the GW through multi-hop communications between APs. We call such a network WIMNET [8,10]. Figure 1.1 illustrates an outline of WIMNET.

As the size of WIMNET increases, the possibility of causing node/link failures increases due to hardware/software faults or network environment changes. If an AP is failed, all of its associated hosts cannot connect to the Internet. Besides, hosts associated with APs at the downstream side of the GW on the routing path may also lose connections. This disconnection problem can be solved by allocating APs redundantly in the field so that redundant APs can back up the failed links/APs [9]. However, these redundant APs are

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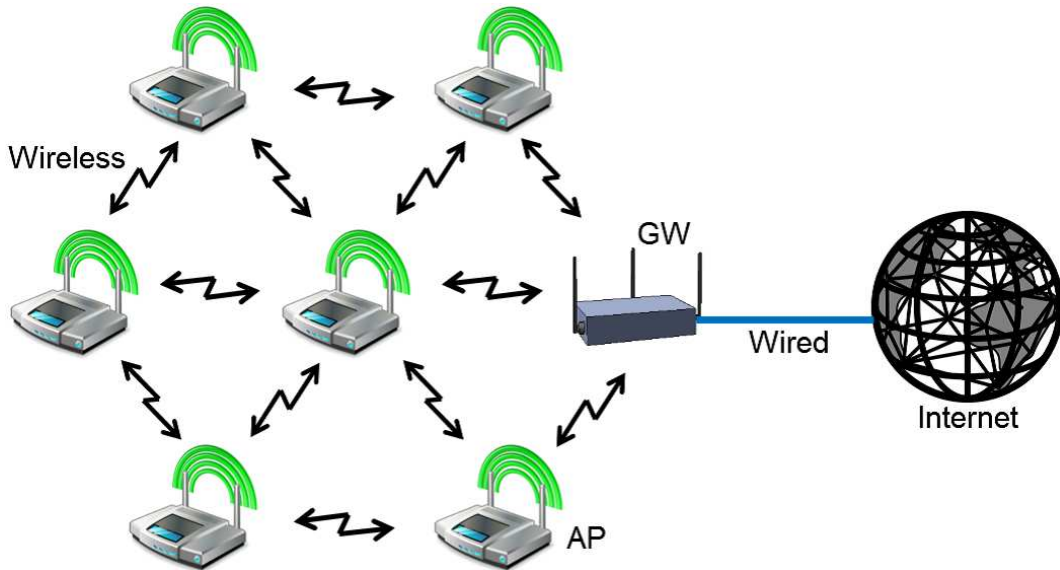
Figure 1.1: Outline of WIMNET.

not necessary in conventional situations where all the APs are functioning properly. If the redundant APs are activated, the operation costs of WIMNET can increase, including the power consumption and the device maintenance [11]. Besides, interferences among APs can increase, which may degrade the performance of WIMNET.

To solve this problem in WIMNET with redundant APs, only the necessary APs should be activated for connections between hosts and the GW. Because the selection of the active APs determines the performance of WIMNET, it becomes an important task for the scalable WIMNET. Therefore, in [8], we defined the *active AP selection problem* as a combinatorial optimization problem, and proposed its heuristic algorithm to select a set of active APs such that the number of active APs is minimized. Then, in [6], we extended this algorithm to consider the dynamic link speed change that has been observed in *IEEE 802.11ac* [12]/*IEEE 802.11n* protocols [13]. The 5 GHz IEEE 802.11ac protocol is a high-speed wireless communication protocol and its backward compatible with the 2.4 GHz IEEE 802.11n standard [14] in most communication devices with backward compatible support. These protocols have become popular to achieve high-speed wireless links and wider signal coverage area by adopting the *multiple-input-multiple-output (MIMO) channel*, the *frame aggregation*, the *channel bonding* and other technologies [12].

Inexpensive commercial products implementing these protocols have become available, including APs and USB WiFi adapters with the WDS function and NICs for personal computers (PCs). Then, WIMNET should adopt them to improve the performance. However, our preliminary experiments using commercial products with the IEEE 802.11n found that the throughput of the link (link speed) is quickly dropped as the distance between the source and destination nodes increases and the receiving signal becomes weak [4]. In [15–17], throughput measurement results using IEEE 802.11ac devices from different vendors have been reported. Particularly, TCP throughputs should be observed because the common network services such as World Wide Webs and emails are using TCP. These results should be used as references for allocations of APs in order to retrieve optimum speeds.

When a scalable WIMNET is implemented using commercial devices, we need to con-

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sider more things. First, multiple GWs should exist in a large-scale WIMNET to increase the capacity of Internet connections. Because every traffic to/from the Internet must pass through a GW, it will become the bottleneck of the whole communications due to the limited capacity of the wireless links around it. This bottleneck should be alleviated by allocating multiple GWs. Second, the number of hops between a GW and a host should be limited for stable multi-hop communications. A larger number of hops can increase the possibility of packet transmission failures due to the delay increase. Some commercial devices implementing IEEE802.11ac limit this number by two [18]. Furthermore, the minimum throughput should be provided to a host to offer QoS when it is exclusively connected to the GW.

1.2 Contributions

In this dissertation, we extend the active AP selection algorithm to efficiently select active APs in WIMNET under the practical conditions.

For the link speed change, we did the experiments by employing IEEE 802.11ac devices from three vendors available in Japan, namely Buffalo, I-O Data, and NEC. The experiments took part both in indoors and outdoors. For indoor experiments, they are used to measure throughputs under different TCP parameters, different number of APs, existences of walls as obstacles along the link path, and different AP positions in a large lecture hall. The devices from Buffalo and NEC are used to measure throughput changes between one-hop and two-hop communications. For outdoor experiments, the devices from the three vendors are used to measure throughput according to different link distances. Furthermore, throughput comparisons are performed between devices using IEEE 802.11ac and devices using IEEE 802.11n.

Then, we extend the *routing algorithm* considering multiple GWs, the hop limitation, and the link speed change in [5] for generating a routing path between the hosts and the GW with the minimal delay [19], because it is used in the active AP selection procedure. In these extensions, we consider the following points for modifications:

1) Any link between a host and an AP is selected in addition to the links between APs, because that speed can be changed. For this purpose, we add the link speed information obtained by measurements or estimations using the host locations into their inputs.

2) Any slow link is excluded from the routing tree by comparing the speed with the given minimum speed.

3) The interference between the two links is judged by comparing the link speed from another transmission node with the given threshold.

To evaluate the extended algorithms, we extend the *WIMNET simulator* [3] to consider the link speed change. Through simulating instances using this simulator, the effectiveness of the extended algorithms is verified.

1.3 Contents of This Dissertation

The remaining part of this dissertation is organized as follows.

In Chapter 2, we introduce related wireless network technology, including IEEE 802.11 protocol, IEEE 802.11n protocol, IEEE 802.11ac protocol, and wireless mesh network.

In Chapter 3, we present the throughput measurements of IEEE 802.11ac/11n WiFi under variable condition.

In Chapter 4, we describe the extended routing algorithm for WIMNET to consider the link speed change.

In Chapter 5, we propose the active AP selection algorithm to consider the link speed change.

In Chapter 6, we extend the WIMNET simulator to simulate the various link speed including the AP-host link.

In Chapter 7, we evaluate the extended active AP selection algorithm and multiple GWs through extensive simulations in multiple instances using the extended WIMNET simulator.

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

Chapter 2

Wireless Network Technology

In this chapter, we briefly introduce four wireless network technologies as backgrounds for this dissertation. First, we overview the *IEEE 802.11 protocol*. Then, we discuss the *IEEE 802.11n protocol* and *IEEE 802.11ac protocol* that are used in experiments as well as simulations. Finally, we outline the WMN that is necessary for the implementation of our proposals.

2.1 IEEE 802.11 Protocol

Nowadays, wireless connectivity for computers, smart phones, tablets are common and virtually all these portable devices come with the latest WiFi connection hardware. The WLAN solutions with operating speeds of $54Mbps$ onwards are available in IEEE 802.11 standard as part of the IEEE 802 family, are able to compete very well with wired network systems. With its high speed performance, flexibility, and portability features, WiFi hotspots are widely available as part of our daily life.

The IEEE 802.11 protocol is a standard created by the IEEE 802 LAN/MAN (Local Area Network/Metropolitan Area Network) Standards Committee. It specifies an over-the-air interface between a wireless client and a base station or between two wireless clients within a local area in either fixed, portable, or moving stations mode [20]. These formation, forms the basic building blocks of an 802.11 networks, named Basic Service Set (BSS). The BSS contains four main physical components: stations, APs (or base stations), wireless medium and distribution system [21].

Figure 2.1 illustrates two types of BSSs block. The independent BSS or ad hoc network, consists of stations communicate directly with each other within the coverage of their communication signal range. While the infrastructure BSS consists of stations communicate through AP [22]. As APs are the main communication medium in infrastructure BSS, thus it's much bigger than the independent BSS.

IEEE 802.11 working group enhances the existing Medium Access Control (MAC) and physical layer (PHY) specification for implementing the WLAN communication in the unlicensed ISM (Industrial, Scientific and Medical) bands defined by the ITU-R (such as 2.4-2.5 GHz , 3.6 GHz and 5.725-5.825 GHz). In this working group, there are several kinds of IEEE Standard Association Standard available, each of them comes with a letter suffix, covers from wireless standards, to standards for security aspects, Quality of Service (QoS) and others as shown in Table 2.1 [23–27].
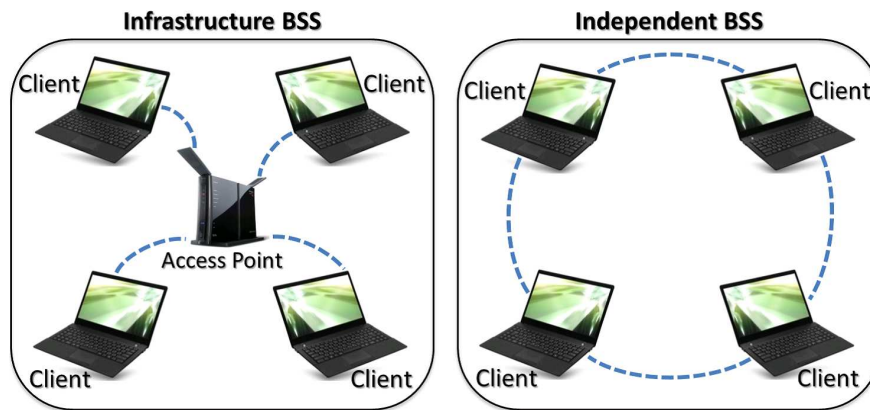
Figure 2.1: Basic Service Sets.

Table 2.1: IEEE 802.11 Standards.

Standard	Purpose
802.11a	Wireless network bearer operating in the 5 GHz ISM band, data rate up to $54Mbps$
802.11b	Operate in the 2.4 GHz ISM band, data rates up to $11Mbps$
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 $54Mbps$
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 $600Mbps$
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

Table 2.1: IEEE 802.11 Standards.

Standard	Purpose
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 IEEE 802.11 MAC for robust audio video (AV) streaming
802.11ac	Wireless network bearer operating below 6 GHz to provide data rates of at least $1Gbps$ for multi-station operation and $500Mbps$ 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
802.11mc	Maintenance of the IEEE 802.11m standard

Figure 2.2 shows the current and future WiFi standards. Among these standards, the most common and popular ones include 802.11a, 802.11b, 802.11g, 802.11n, and the latest 802.11ac. For the physical layer, the 802.11a/n/ac use Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme while the 802.11b uses the Direct Sequence Spread Spectrum (DSSS) technology. 802.11g supports both technologies. Table 2.2 shows the comparison between these common WiFi standards. The following section discusses 802.11n and 802.11ac in detail.
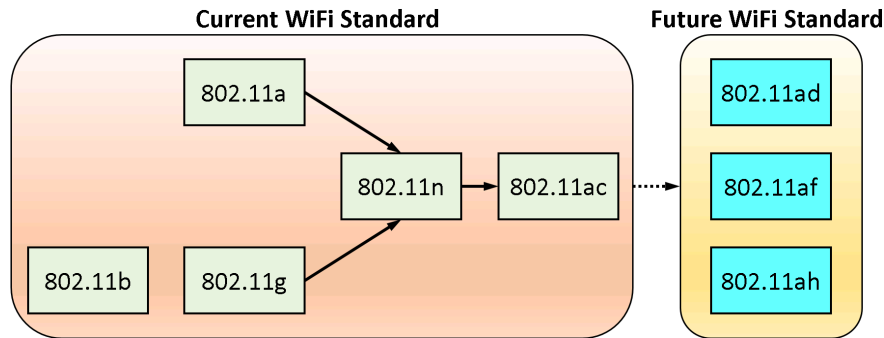
Figure 2.2: Current and future WiFi Standards.

Table 2.2: Common IEEE 802.11 WiFi Standards.

Standard	Max Data Rate (Mbps)	Frequency Band (GHz)	Bandwidth (MHz)	Modulation Scheme	Spatial Streams
802.11a	54	5	20	OFDM	1
802.11b	11	2.4	20	DSSS	1
802.11g	54	2.4	20	OFDM/DSSS	1
802.11n	600	2.4/5	20/40	OFDM	4
802.11ac	1300	5	20/40/80/160	OFDM	8

2.2 IEEE 802.11n Protocol

In this section, we overview the IEEE 802.11n protocol and our throughput measurement results using commercial devices implementing this protocol. IEEE 802.11n is an amendment to the IEEE 802.11 2007 wireless networking standard. This standard was introduced with 40 MHz bandwidth channels, MIMO, frame aggregation, and security improvements over the previous 802.11a, 802.11b, and 802.11g standards. Table 2.3 shows a brief summary of this standard.

Table 2.3: IEEE 802.11n specification.

Specification	IEEE 802.11n	
Frequency Band	2.4 GHz	5 GHz
Simultaneous Uninterrupted Channel	2 ch	9 ch
Available Channel	13 ch	19 ch
Max Speed	$600 Mbps$	
Max Bandwidth	40 MHz	
Max Spatial Streams	4	
Subcarrier Modulation Scheme	64 QAM	
Release Date	Sept 2009	

We can use the IEEE 802.11n in either the 2.4 GHz or 5 GHz band. Nowadays, the 2.4 GHz is very popular as it was inherited from the 802.11g. This frequency band has become crowded with lots of WiFi signal using the same channel. As a result, these similar WiFi with adjacent channel overlapping will suffer from interference between each other and end up with throughput performance degrade.

For 2.4 GHz band, there are limited simultaneous uninterrupted channels that are free from channel overlapping, which are Channel 3 and Channel 11 in 40 MHz bandwidth. While for 20 MHz bandwidth, Channel 1, Channel 6, and Channel 11 are free from interference. In overall, wider bandwidth will reduce the amount of available free channel. Figure 2.3 [27] shows the WiFi channels for IEEE 802.11n 2.4 GHz band.
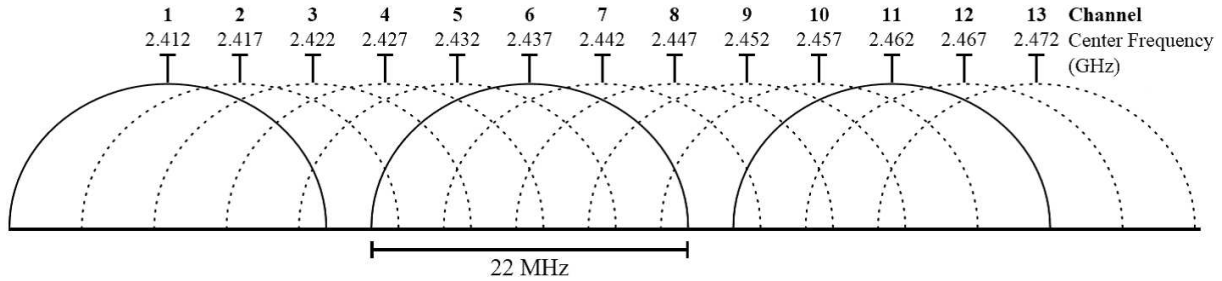
Figure 2.3: WiFi channels in 2.4 GHz band.

For IEEE 802.11n in 5 GHz band, it has a total of 19 simultaneous uninterrupted channel available in 20 MHz bandwidth. While in 40 MHz bandwidth, which doubles the channel width from 20 MHz, there are nine channels. For 80 MHz bandwidth, there are four of them. Figure 2.4 [28] shows these WiFi channels for the IEEE 802.11n 5 GHz band.
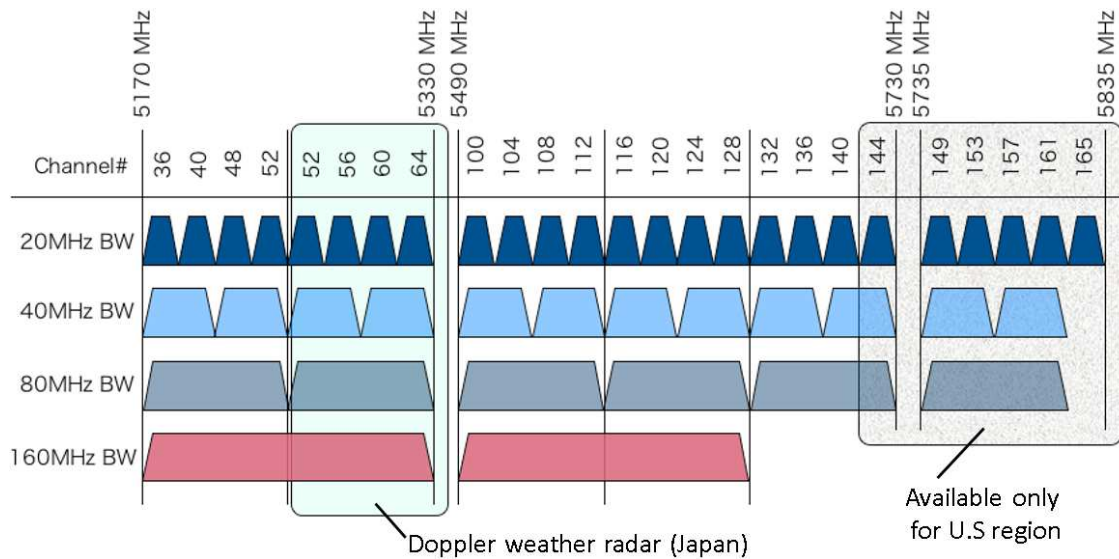
Figure 2.4: WiFi channels in 5 GHz band.

Both IEEE 802.11n 2.4 GHz and 5 GHz retain the common 20 MHz channel bandwidth used by the previous 802.11 standards. Through the concept of channel bonding, whereby two 20 MHz channels are combined into a single 40 MHz channel, the 802.11n had benefited in higher transmission rates [29]. However, the usage of channel bonding will reduce the available channels for other devices as there are only two channels available for 802.11n 2.4 GHz. Table 2.4 shows the usage of different channel bandwidth and spatial stream towards the throughput of IEEE 802.11n.

In 802.11n, a total of four spatial streams are used to transmit up to $150Mbps$/stream and reach the maximum data rate (throughput) of $600Mbps$ through the MIMO technology. MIMO uses multiple antennas to transmit multiple spatial data streams through Spatial

Table 2.4: Effects of channel bandwidth and spatial stream's selection towards IEEE 802.11n's throughput.

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

Division Multiplexing (SDM), within one spectral channel of bandwidth. Figure 2.5 shows the comparison between the previous technologies, Single Input Single Output (SISO) transmission and MIMO transmission. SISO uses one transmit antenna and one receive antenna, whereby 802.11n uses up to four transmit and receive antennas between devices. SISO system allowed only one antenna, active during data transmissions, while all antennas in the MIMO system are active simultaneously [30].
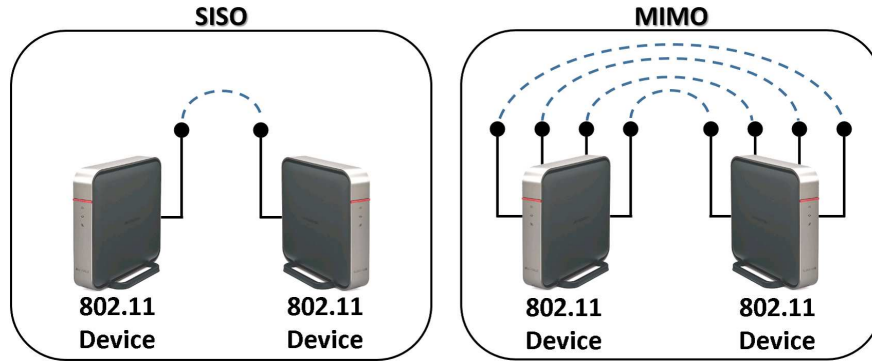
Figure 2.5: Comparison between SISO transmission and MIMO transmission.

Besides the introduction of MIMO, 802.11n also provides performance improvement through frame aggregation in the MAC layer. Frame aggregation can transmit multiple frames by one big frame with a single pre-ample and header information to reduce the overhead by them.

802.11n introduces the Aggregation of MAC Service Data Units (A-MSDUs) and Aggregation of MAC Protocol Data Units (A-MPDUs). Frame aggregation is a process of packing multiple A-MSDUs and A-MPDUs together to reduce the overheads and average them over multiple frames, thereby increasing the user level data rate [31].

While in the physical layer, 802.11n use the 64 Quadrature Amplitude Modulation (QAM) scheme under the Modulation and Coding Scheme (MCS). QAM is a form of modulation technique used for modulating digital information signals. QAM exists in both analogue and digital formats. For 802.11n, the digital QAM format is used and named as Quantized QAM. In QAM, digital information is encoded in bit sequences represented by discrete amplitude levels of an analog carrier. Two carriers are shifted in phase of 90° with output varies in both amplitude and phase. For 64 QAM, six bits of input alters the phase and amplitude of the carrier to generate 64 modulation states.

2.3 IEEE 802.11ac Protocol

In this section, we overview the IEEE 802.11ac protocol and our throughput measurement results using commercial devices implementing this protocol. IEEE 802.11ac is an amendment to the IEEE 802.11 2007 wireless networking standard. This standard was introduced with 5 GHz frequency band, 160 MHz bandwidth channels, MU-MIMO, increased number of spatial stream, and higher order of modulation over the previous 802.11n standards. Table 2.5 shows a brief summary about this standard.

Table 2.5: IEEE 802.11ac specification.

Specification	IEEE 802.11ac
Frequency Band	5 GHz
Simultaneous Uninterrupted Channel	9 ch
Available Channel	19 ch
Max Speed	6.93 Gbps
Max Bandwidth	160 MHz
Max Spatial Streams	8
Subcarrier Modulation Scheme	256 QAM
Release Date	Dec 2012

IEEE 802.11ac 5 GHz band having the same WiFi channels with IEEE 802.11n 5 GHz, as shown in Figure 2.4. In this frequency band, there are nine simultaneous uninterrupted channels using 40 MHz bandwidth that is free from channel overlapping and interference between each other. For 80 MHz bandwidth, which doubles the channel width from 40 MHz, there are four channels while for 160 MHz bandwidth, there will be two of them. These IEEE 802.11ac WiFi channels are same with the 5 GHz IEEE 802.11n, as shown in Figure 2.4.

Channel Bonding can increase the data transmission capacity by bonding two or more adjacent channels into one channel. 802.11ac allows to bond maximally eight 20 MHz channels into one 160 MHz channel. Besides, 802.11ac assigns 234 sub-carriers at one 20 MHz channel, whereas the previous 802.11n standard does 108 sub-carriers there [13]. This sub-carrier increase can also enhance the data capacity by more than twice.

Take note that, within a crowded environment, if multiple 802.11ac's APs are in use, the non-overlapping channels will drop down to 9, 4 and 2 channels when using channel bonding for the bandwidth of 40 MHz, 80 MHz, and 160 MHz respectively. In order to avoid interference between APs, lower channel bandwidth will provide fairer performance for all users. Table 2.6 shows the usage of different channel bandwidth and spatial stream towards the throughput of IEEE 802.11ac.

In 802.11ac, a total of eight spatial streams are used to transmit up to $866.7Mbps$/stream and reach the maximum data rate (throughput) of $6,933Mbps$ through the MIMO technology. MIMO can transmit multiple data in parallel by adopting multiple antennas. For example, when the source node and the destination node have two antennas respectively, the transmission speed becomes doubled using two data streams. 802.11ac allows the maximum of eight antennas.

Besides that, 802.11ac also comes with the MU-MIMO, which allows an AP to transmit data to multiple hosts in a parallel way without interferences between them by adopting the

Table 2.6: Effects of channel bandwidth and spatial stream's selection towards IEEE 802.11ac's throughput.

Stream Number	Bandwidth			
	20 MHz	40 MHz	80 MHz	160 MHz
1 Stream	$86.7Mbps$	$200Mbps$	$433.3Mbps$	$866.7Mbps$
2 Streams	$173.3Mbps$	$400Mbps$	$866.7Mbps$	$1733Mbps$
3 Streams	$288.9Mbps$	$600Mbps$	$1300Mbps$	$2340Mbps$
4 Streams	$346.7Mbps$	$800Mbps$	$1733Mbps$	$3466Mbps$
8 Streams	$693.4Mbps$	$1600Mbps$	$3466Mbps$	$6933Mbps$

beamforming technology that generates directional radio signals. This is far faster than the serial communication in the 802.11n standard. MU-MIMO can realize 1-to-n data transmissions using the same band.

Apart from the MU-MIMO, 802.11ac also introduced with the beamforming technology. In beamforming, a sender detect where the receiver are and transmits data through intensifying the signal in their direction(s). The focus of radio frequency energy towards the receiver will provide higher signal strength to increase the speed. This is better than the traditional way of broadcasting wireless signal equally in omni directions. Figure 2.6 shows the different between the usage of beamforming technology and normal WiFi.
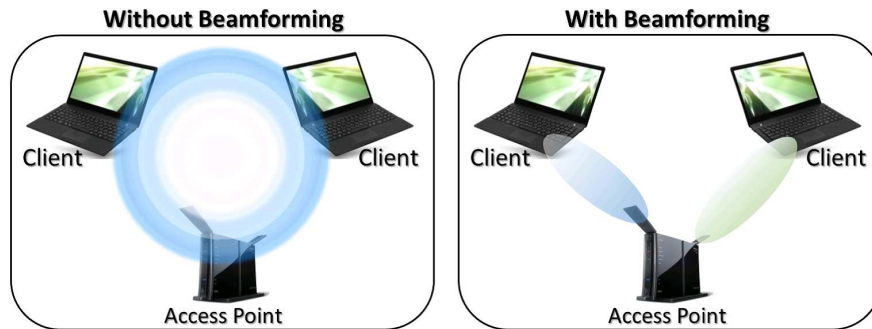
Figure 2.6: Beamforming technology.

The 802.11ac also inherits the A-MSDU and A-MPDU from 802.11n, and allows the maximum of 1 Mbyte for one frame, whereas 802.11n does 64 Kbyte.

In order to gain higher transmission rate, the Guard Interval (GI) that represents the period between two consecutive packet transmissions of 802.11ac also has been reduced. It is necessary to avoid interferences between them that can be caused by the delay of the first packet arrives at the destination node. 802.11ac adopts 400 ns as the guard interval time, whereas 11a/g does 800 ns.

In the physical layer, 802.11ac use the 256 QAM scheme under the MCS. In 256 QAM, eight bits of input alters the phase and amplitude of the carrier to generate 256 modulation states. Figure 2.7 shows the comparison between 64 QAM constellation (IEEE 802.11n) to the 256 QAM constellation.
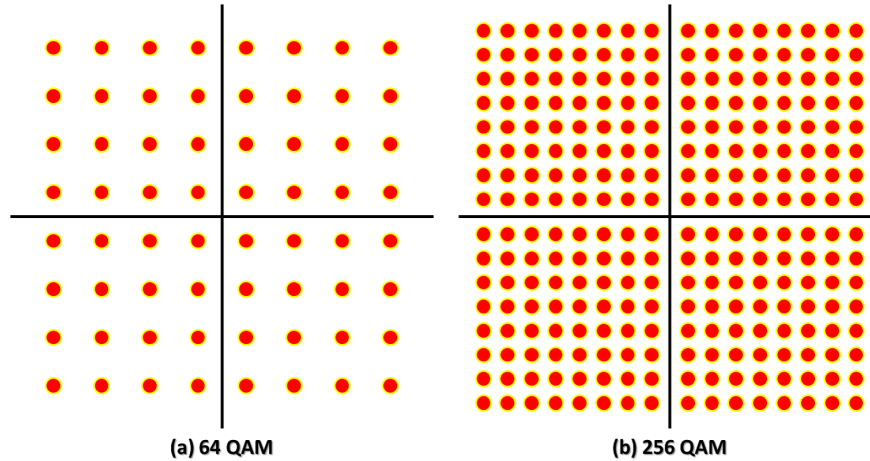
Figure 2.7: Comparison of modulation.

2.4 Wireless Mesh Network

WMN as an emerging technology, may replace the inconvenience wired LAN and brings portability to everyone and even everywhere. WMN, mentioned as the IEEE 802.11s standard, was an amendment to the IEEE 802.11 2007 wireless networking standard. This standard mentioned about the wireless LAN MAC and PHY specifications for WMN [32].

The conventional mesh network comes in multi LAN connection arrangement with partial (not all clients are directly interconnected) or full mesh (every client is directly connected to all other clients) topology. WMN was formed using the connection of mesh routers installed at various fixed network points.

WMN consists of two types of nodes: mesh routers and mesh clients. Mesh routers and conventional wireless routers having similar functions except the extra routing function for mesh networking [2]. They can be in the form of fixed (located on rooftop/outside the building) or mobile (inside vehicles). Every mesh router has redundant multiple wireless links with other mesh routers in order to forward data through multi-hop method [33].

For the mesh clients, they can be either stationary or mobile clients with only one type of wireless link function. They connect to WMN through mesh routers. Examples of mesh clients including smart phones, notebook computers and tablet PCs. Figure 2.8 shows an example of WMN that connects to the Internet through the gateway.

WMN does not tie to any types of wireless standard. It could be a mixture of 802.11n, 802.11ac, and many others. It does not depend on any infrastructure. Therefore, its application is widely available in the following scenarios [2, 33–35]:

- *Connectivity*: To provide proper network connection at every mesh router.

- *Broadband Internet access*: To be served as a middleman between the Internet service provider and end user.

- *Mobile user access*: To provide high speed data connection to mobile users.

- *Indoor WLAN coverage*: To provide complete WiFi coverage at every corner inside the building.
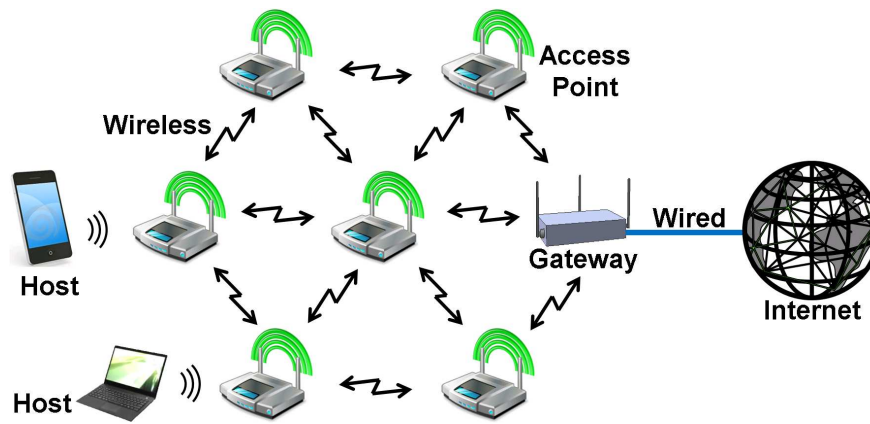
Figure 2.8: Wireless mesh networks.

- *Broadband home networking*: To provide usage of mesh router to provide full networking coverage at a home.

- *Building automation*: To provide monitoring and controlling of variety electrical devices inside a building.

- *Community and neighborhood networking*: Implementation of flexible mesh connection between home.

- *Enterprise networking*: Mesh network within an office, an entire office building, or big size buildings.

- *Campus networking*: Mesh network within a university's campus for the usage of staffs and students.

- *Metropolitan area networks*: Big size mesh networks in one or more urban areas.

- *Transportation systems*: To provide transportation support and traffic information to all types of transport from land to water.

- *Health and medical systems*: To ease the transmission of huge critical data from medical devices to the server.

- *Security surveillance systems*: To increase the monitoring area's coverage at all locations.

- *Spontaneous (emergency/disaster) networking and peer-to-peer communications*: To provide wireless network for emergency response.

- *Vehicular ad hoc networks (VANETs)*: Cars are used as mesh clients in order to communicate with each other for safety purposes.

- *Wireless sensor networks (WSNs)*: User will be able to remotely monitor and control all electronic devices.

In this dissertation, a simple form of WMN named *WIMNET* is studied. The next chapter discusses the throughput measurements that will be used WIMNET. Chapter 4 discusses the active AP selection algorithm for WIMNET.

Chapter 3

Throughput Measurement

In this chapter, we provide various TCP throughput measurement results using devices from three vendors implementing this protocol in various conditions including comparison of throughput between indoor and outdoor, one-hop and two-hop communications, effects of walls, effect of IEEE 802.11ac repeater, comparison of throughput in lectures hall with different access point (AP) locations, and effects of link distance. As a comparison, we also conduct the tests in IEEE 802.11n as well.

3.1 Measurement Setups

In this section, we explain the experimental setups for TCP throughput measurements using IEEE 802.11ac and IEEE 802.11n devices. There are three items to be taken into consideration as shown below before conducting the throughput measurement.

  i Measurement Site Setup

 ii Hardware Setup

iii Software Setup

3.1.1 Measurement Site Setup

Several experimental sites within Okayama University campus were selected to conduct our tests. For the indoor parts, we have chosen several rooms and a corridor area near our laboratory. We also conducted the measurements at a big lecture hall. As for the outdoor parts, we chosen the open space nearby our laboratory building.

3.1.1.1 Indoor Sites

For indoor experiment sites, we selected rooms and a corridor in our building (Engineering Building 2) as in Figure 3.1 and Figure 3.2. Several tests were conducted in the room and in between rooms in order to consider the actual possible usage of WiFi in the room(s).

The tests near the corridor, simulate possible usage of WiFi while user are around that area. Figures 3.3 and Figure 3.4 show these area's throughput tests in both one-hop and two-hop configurations.

Figure 3.1: Hosts for indoor experiments in room.

Figure 3.2: Server and host for indoor experiments in corridor.
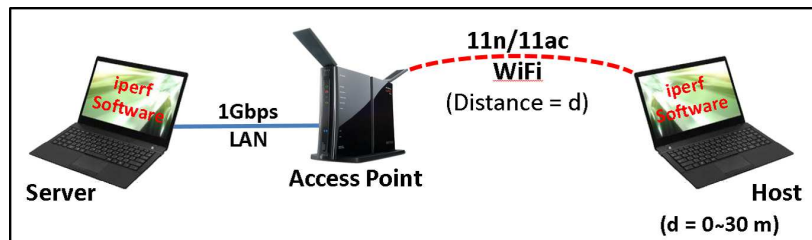
Figure 3.3: Indoor one-hop tests along corridor area.
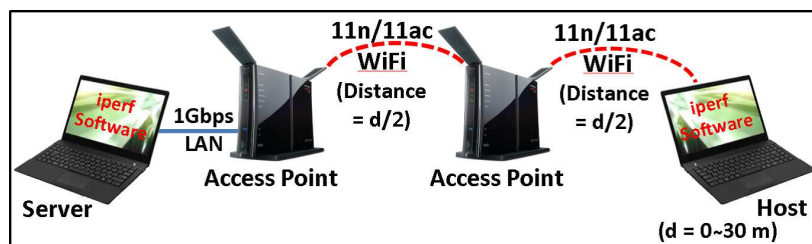
Figure 3.4: Indoor two-hop tests along corridor area.

To measure throughput drops by walls in indoor sites, we selected three types of setups. In the first setup, we measured throughputs between three rooms partitioned by concrete walls in Figure 3.5 with/without the effects of a repeater in the middle room.

In the second setup, we measured throughputs between three rooms partitioned by concrete walls. Here, we measured throughputs at fixed distances of $8m$ between both host-AP and AP-AP configuration in Figure 3.6. We did the measurement using IEEE 802.11n and IEEE 802.11ac devices from three vendors to evaluate the effects of wall obstacles towards

WiFi signal. We also repeated the same tests under one wall and no wall condition as shown in Figure 3.7 and Figure 3.8.
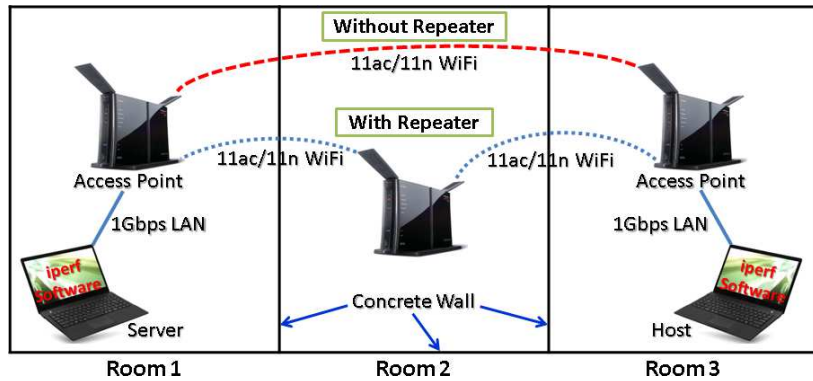
Figure 3.5: Indoor experiments setup in three rooms with/without repeater effects.
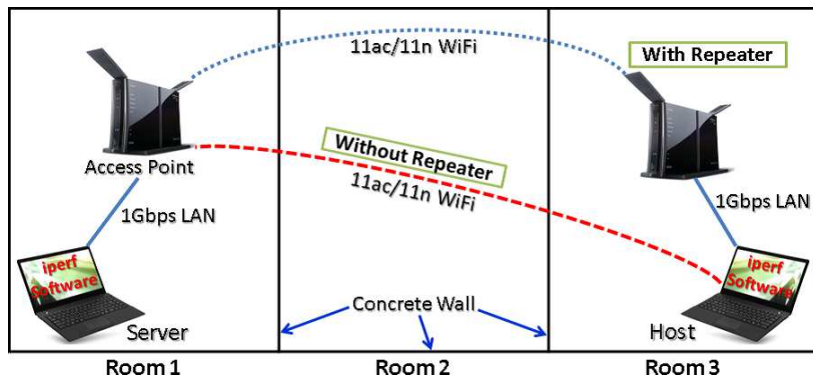
Figure 3.6: Two wall tests - host to AP/AP to AP.
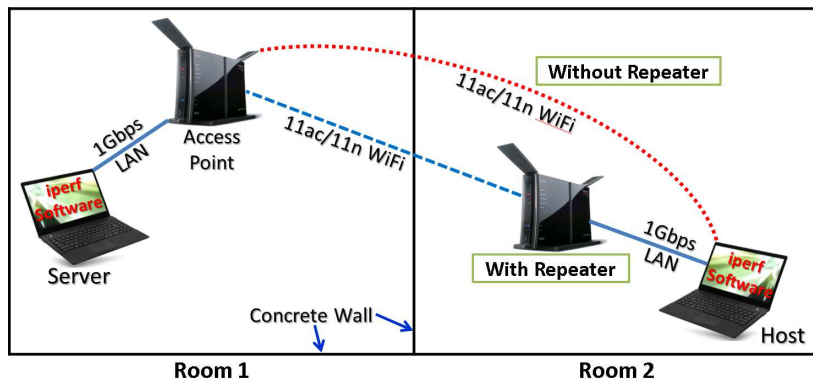
Figure 3.7: One wall tests - host to AP/AP to AP.

In the third setup, we measured throughputs between two rooms partitioned by one concrete wall. Here, we measured throughputs in both one-hop and two-hop communications using the combination of IEEE 802.11n and IEEE 802.11ac devices to evaluate the use of an IEEE 802.11ac repeater for IEEE 802.11n hosts as shown in Figure 3.9.
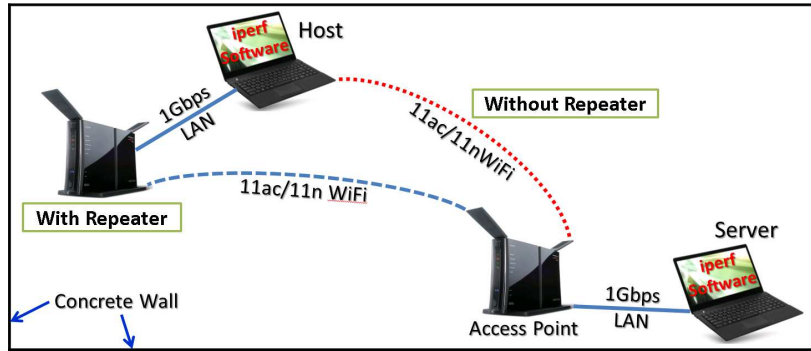
Figure 3.8: No wall tests - host to AP/AP to AP.
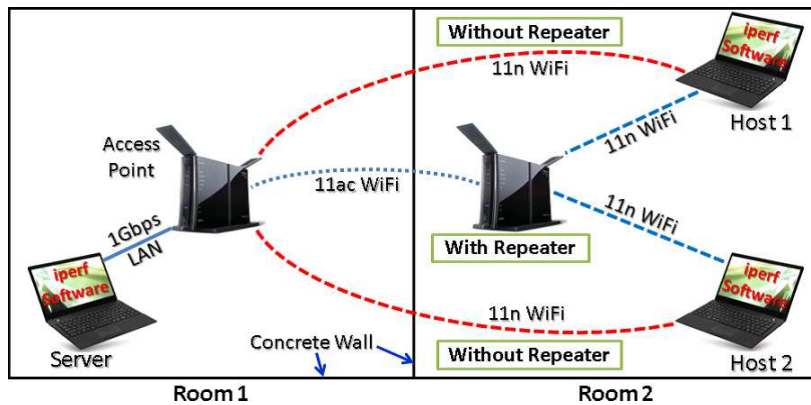
Figure 3.9: Indoor experiments setup with/without IEEE 802.11ac repeater in two rooms.

3.1.1.2 Lecture Hall Site

Besides the throughput measurements in small rooms, we selected a large lecture hall with the size of $17.53m \times 15.30m$. In order to cover the whole area of this room, nine hosts are placed regularly to simulate possible positions of users. We had divided the experiments into two types of cases, namely the ideal case and practical case. Both cases are tested with multiple APs simulated as GWs.

For ideal case, in order to gain the highest throughput for one-AP case, we placed this AP in the middle of the room as shown in Figure 3.10. For two-AP case, we divided the hosts into two groups and placed the AP in the middle of each group as shown in Figure 3.11.
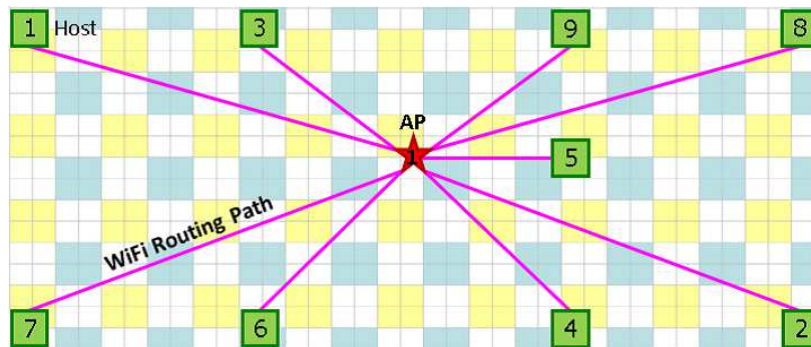
Figure 3.10: One AP topology for ideal AP location.
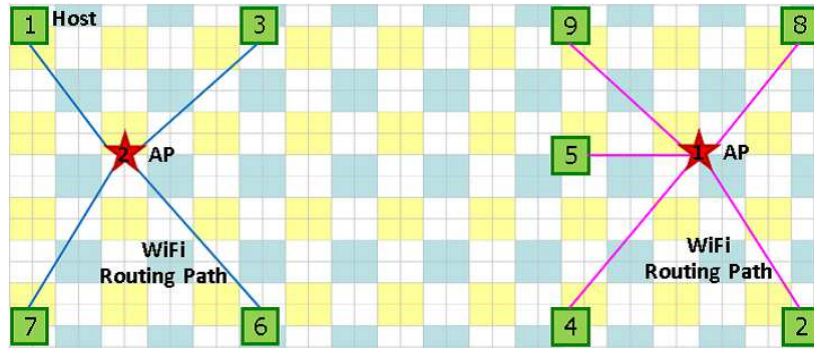
Figure 3.11: Two APs topology for ideal AP location.

In practical cases or real situations, any AP must be placed nearby the Internet LAN cable port, and should not be an obstacle for the big lecture room user. Thus, we placed the one to three APs at the corner of the room at the Internet port as shown in Figure 3.12. The hosts are associated with one AP among them such that the number of hosts is nearly equal among the APs.
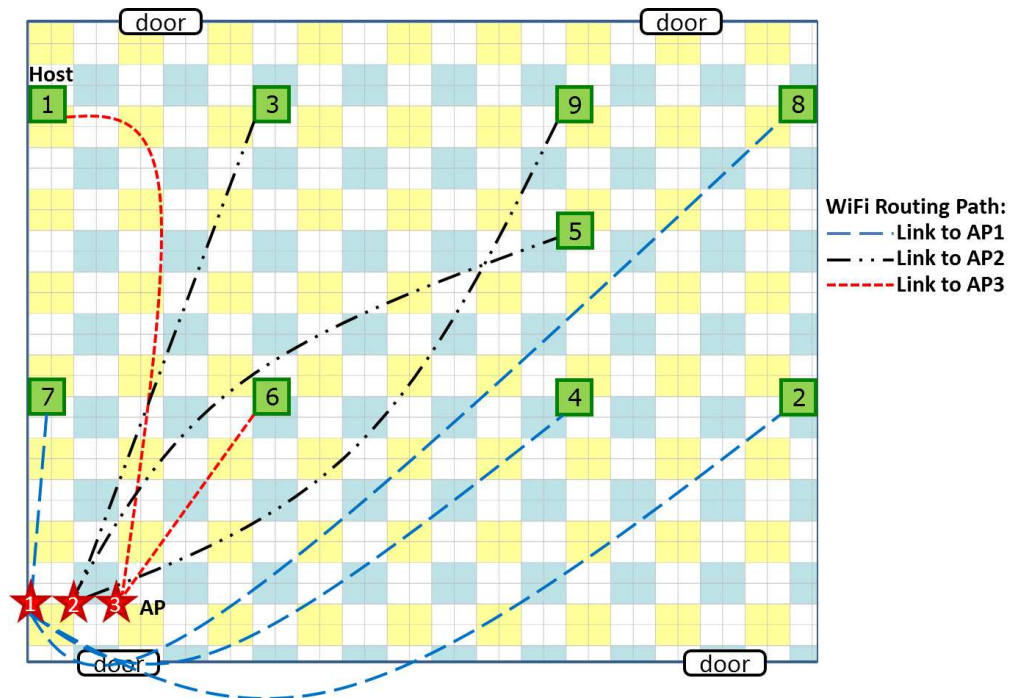
Figure 3.12: Three APs topology for practical AP location.

In the same building, we also measured the throughput drops by wall obstacles between the lecture hall and open space area as shown in Figure 3.13. At the open space area, the mobile host/AP will move from $5m$ to $30m$ from the server station located in the lecture hall. This condition simulates the performance of Internet usage from the AP located in the lecture hall.
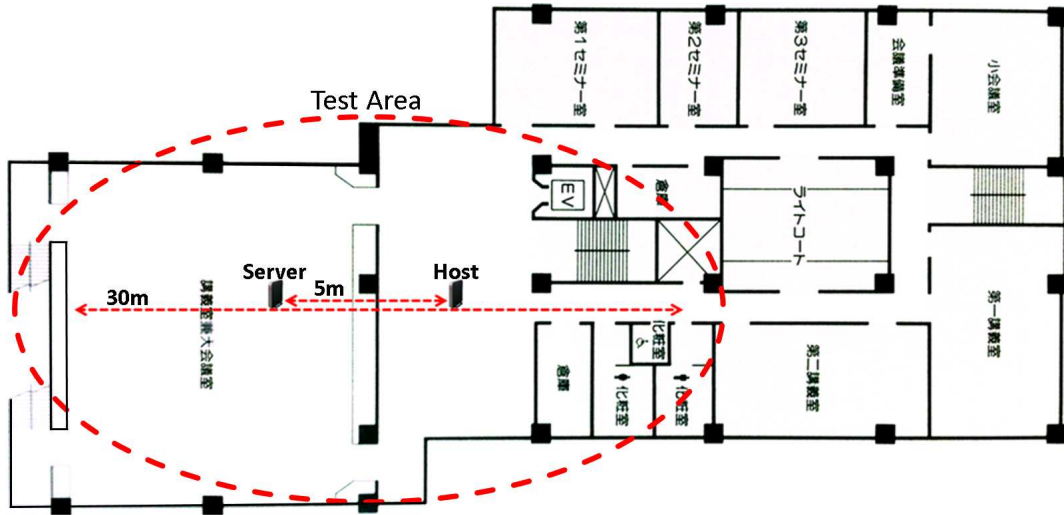
Figure 3.13: One wall tests at lecture hall.

3.1.1.3   Outdoor Site

For the outdoor experiment site, we selected the open space in the campus near our building in Figure 3.14. We conducted the tests using IEEE 802.11ac and IEEE 802.11n using Buffalo APs as shown in Figure 3.15 and Figure 3.16.

Figure 3.14: Server and host for outdoor experiments in campus.
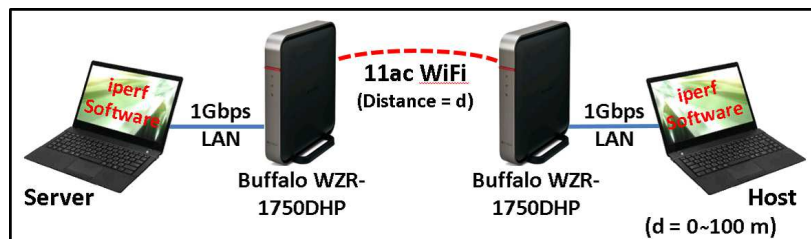
Figure 3.15: IEEE 802.11ac outdoor tests.

Started from $0m$, the mobile host will move with $5m$ interval to $100m$ from the fixed server station. The maximum transmission range has been fixed in $100m$ due to IEEE 802.11n having poor connection that is no longer suitable for stable Internet connection even though IEEE 802.11ac still able to maintain good throughput rate. We also did the
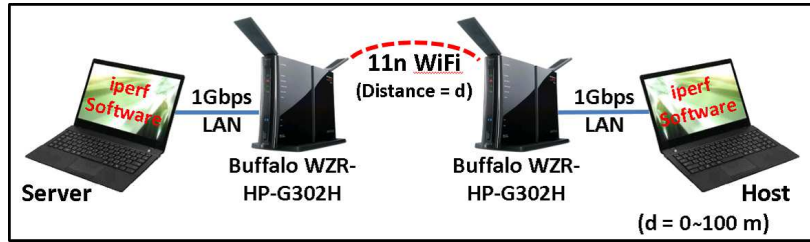
Figure 3.16: IEEE 802.11n outdoor tests.

comparison tests using three IEEE 802.11ac vendors with Buffalo AP, I-O Data AP, and NEC AP as well as their respective USB WiFi adapter.

3.1.2 Hardware Setup

In this section, we explained the hardware setups for TCP throughput measurements using IEEE 802.11ac and IEEE 802.11n devices as shown as follow:

- Access-Point

- USB WiFi adapter

3.1.2.1 Access-Point

For IEEE 802.11n, we adopted APs from Buffalo WZR-HP-G302H and WZR-1750DHP. For IEEE 802.11ac, we adopted APs from Buffalo WZR-1750DHP, I-O Data Air Port WN-AC1600DGR, and NEC Aterm WG1800HP, with reference to the AP's uses as per below is performed.

- Set IEEE 802.11ac at the 5 GHz frequency with 80 MHz bandwidth.

- Set IEEE 802.11n at the 2.4 GHz frequency with 40 MHz bandwidth.

- Set common Local Area Network (LAN) side IP address for every AP's configuration login page.

- Set common WLAN's Service Set Identifier (SSID), encryption type and encryption key for all experiments.

- Set WLAN type and channel number for different types of experiment.

- Disable SSID broadcasts during experiment to avoid unnecessary connection and interference.

- Update the AP's firmware through the AP's login page at Internet web browser.

3.1.2.2 USB WiFi Adapter

In the throughput experiment, build-in IEEE 802.11n WiFi device in the notebook PC enable user to directly communicate to an AP. However, USB WiFi devices for IEEE 802.11ac, namely Buffalo WI-U2-866D[36], I-O Data WN-AC867U[37], and NEC Aterm WL900U[38]. Devices from the same AP vendor were used for any experiment needed to be connected through a USB port.

For a standard notebook PC, the numbers of available USB port would be around two to three. They might be located in front of the notebook or beside the notebook (left or right side) in Figure 3.17.

(a) above ventilation holes.　　　　　　　　(b) besides the audio ports

Figure 3.17: Location of USB port on a notebook PC.

Some notebook PCs have their USB ports located nearby the ventilation hole or heat exhaust in Figure 3.17a. Heat generated from the CPU and GPU's of the notebook will be exhausted away, towards these ventilation holes and heat up these areas [39]. Take note that when we plug in the USB WiFi adapter at the USB port near these area, the USB device itself becomes very hot and it might exceed its standard operating environment's temperature of 0-40°C (32-104°F). In order to avoid any operating error, we selected those USB port without any nearby ventilation hole in Figure 3.17b.

3.1.3 Software Setup

In this section, we explain the software setups as shown as follows for TCP throughput measurements using IEEE 802.11ac and IEEE 802.11n devices.

- Windows 7

- Network optimization in Windows 7

- Host and server optimization

- Verify wireless networks

- Wireless network interference

- Thermal fade interference

- iperf

3.1.3.1 Windows 7

During the throughput tests, a notebook PC using Microsoft Windows 7 operating system was chosen due to its portability instead of a desktop PC. In order to maintain the high performance of a notebook PC as well as its network speed, multiple steps will be taken into consideration.

There are lots of system-based and user installed software that running during the startup of Microsoft Windows 7 operating system. These programs may take up the system resources and some of them might even use the network bandwidth to check for update as well. In order to obtain better network throughput results, all these startup programs should be disabled during the test. In order to disable the startup programs, firstly, open the start menu, type the word "msconfig", and select the program "msconfig.exe" in order to open the System Configuration program.

From the System Configuration program, select the Startup tab in Figure 3.18. Then, click on the "Disable all" button, and click the "OK" button. Restart the computer to complete this process.
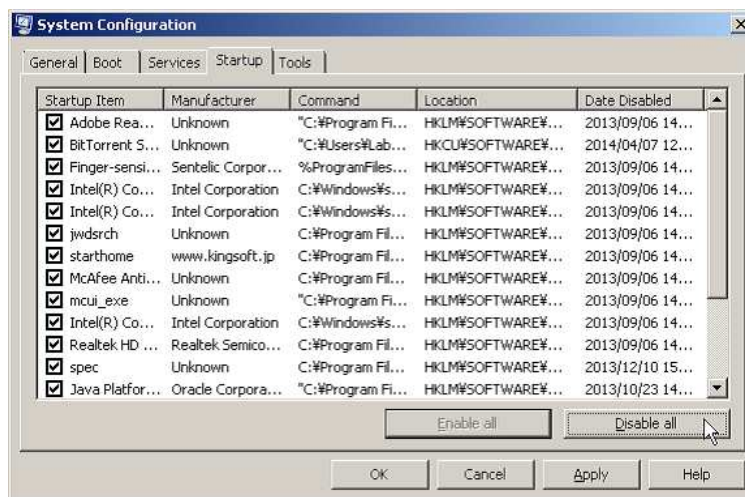
Figure 3.18: The Startup tab in System Configuration.

3.1.3.2 Network Optimization in Windows 7

Besides disable all unnecessary startup programs in the operating system, the configuration of all network adapters (both build-in or external type) in the notebook PC can be optimized with the SG TCP Optimizer version 3.0.8 from Speed Guide, Inc.[40] in Figure 3.19. This network optimizing process will ensure that all network adapter's Maximum Transmission Unit (MTU) values are set to 1500 bytes [21] instead of default value at 0 bytes in Microsoft Windows 7. In order to optimize all network adapters (both build-in or external type), the USB WiFi that is used during the measurement must be plugged into the notebook PC with its related software driver installed first.

From the first tab of this program, the "General Settings" tab, check the "Modify All Network Adapters" box and also select the "Optimal" choice under the "Choose settings" options. Then, click the "Apply changes" button. A new window will pop up showing all related changes that are going to make towards the network adapters, click the "OK" button
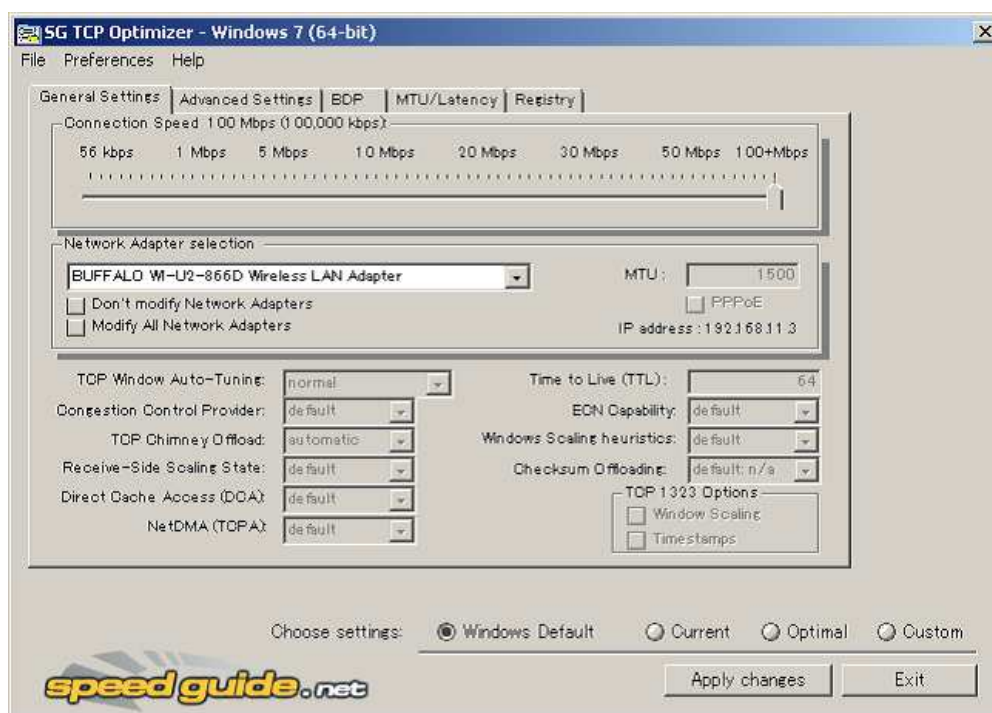
Figure 3.19: SG TCP Optimizer version 3.0.8.

to continue. Next, another new window will pop up, click the "OK" button again to continue reboot the computer in order to complete the optimizing process.

The network optimizing of USB WiFi adapter (and any build-in WiFi adapter as well) will be taken into consideration with condition the USB WiFi adapter using the same USB port during the whole test for particular time. If the USB WiFi adapter is plugged into another USB port, this optimizing process must be executed again in order to optimize network settings for this device. Besides, this network optimizing process should be executed every time Microsoft Windows 7 boots up, to ensure that all network parameter values are set to optimal value instead of default non optimum value.

3.1.3.3 Host and Server Optimization

Before the beginning of any types of throughput test, all 9 hosts (clients) must be connected to their respected AP's WiFi network by referring to [41]. They must be preconfigured with customized IP address, subnet mask, default gateway and preferred DNS server address, as shown as follows. Customized IP address is used in order to record the throughput for every host and AP.

- IP address for host 1 to host 9: Ranging from 192.168.11.31 to 192.168.11.36 and 192.168.11.51 to 192.168.11.53

- Subnet mask address: 255.255.255.0

- Default gateway address: 192.168.11.1 (For AP1), 192.168.11.2 (For AP2), 192.168.11.3 (For AP3)

- Preferred DNS server address: 192.168.11.54

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As for the server side, customized IP address, subnet mask, default gateway and preferred DNS server address as shown as follows were used throughout the tests. These network address details could be entered by referring to steps stated for hosts.

- IP address: 192.168.11.54

- Subnet mask address: 255.255.255.0

- Default gateway address: 192.168.11.1

- Preferred DNS server address: 192.168.11.54

3.1.3.4   Verify Wireless Networks

After a host established WiFi connection with a related AP, we can add/delete these network, change their priority and security features in "Manage wireless networks" windows in Figure 3.20.
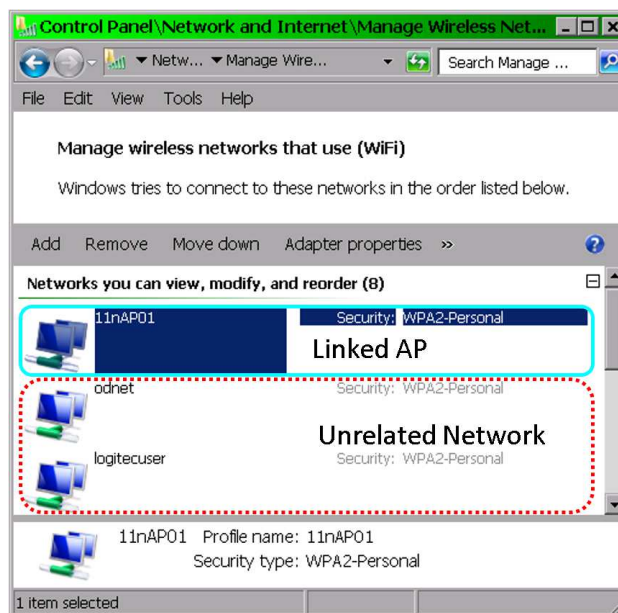
Figure 3.20: Manage wireless networks.

To reach this window in Windows 7, first, enter the Control Panel from the Start Menu. In the Control Panel window, click "Network and Sharing Center", then select "Manage wireless networks" at the left hand side column. Here, we should remove all unrelated WiFi networks as well in order to avoid incorrect connections.

By selecting any one of the networks listed in the window, right click on that network and click on the "Properties" option. From Figure 3.21, check on the third option, "Connect even if the networks is not broadcasting its name (SSID)", so that the host is able to connect to the AP that are using hidden SSID.

3.1.3.5   Wireless Network Interference

During the experiments, especially at indoor site, we observed lots of WiFi signals with our devices (AP). They might be sourced from the WiFi APs from rooms in the test location,
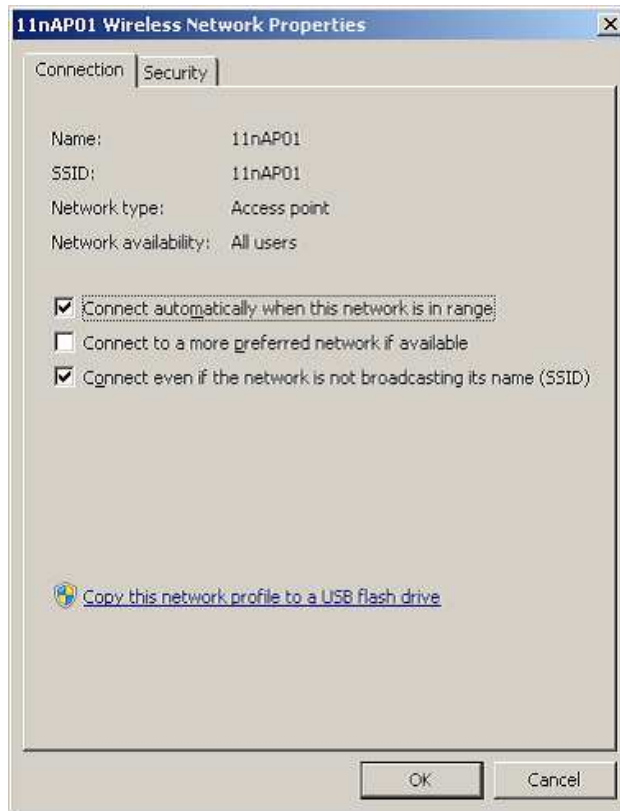
Figure 3.21: 11nAP01 wireless network properties - connection.

university's WiFi network APs, or other devices such as cordless phones or microwaves having the same frequency [42]. These interferer might cause interferences [43–46]. According to [47], even an interfering signal that is 1,000 times weaker than the AP's signals can disrupt the vulnerable IEEE 802.11 link easily.

As for the outdoor site, we observed the WiFi interferences mostly from public WiFi and Internet service provider's based transmission stations. Besides, we faced significant unavoidable physical signal interferences from passerby movements between transmitters and receivers [48, 49] that caused lower throughputs due to non-line-of-sight communications [50]. In order to reduce the effects of these interferences, several steps are being taken into consideration.

Depending on our experiment type, whether in 2.4 GHz or 5 GHz frequency, we will scan the available WiFi signals at the experiment site using both notebook PC and smart phone. In the notebook PC, we used Wi-Fi Channel Scanner software in Figure 3.22 from www.wifichannelscanner.com to detect such wireless networks. It is a real-time signal scanner for the current WiFi hotspot that provides related network names/SSID, channels, signal quality, and other information.

For the Android based version 4.2.2 operating system smart phone, we used WiFi Analyzer from Farproc to check currently available channel for our AP(s). This software shows both 2.4 GHz and 5 GHz as in Figure 3.23. This application provides better portability as it allows the user to move around the test site to check the whole area. For the iOS based operating system, the WiFi Explorer v1.1 from Granados and WiFiForum from www.dynamicallyloaded.com can be used to scan currently available WiFi signal and its channel. Both software require jailbreak version of iOS.
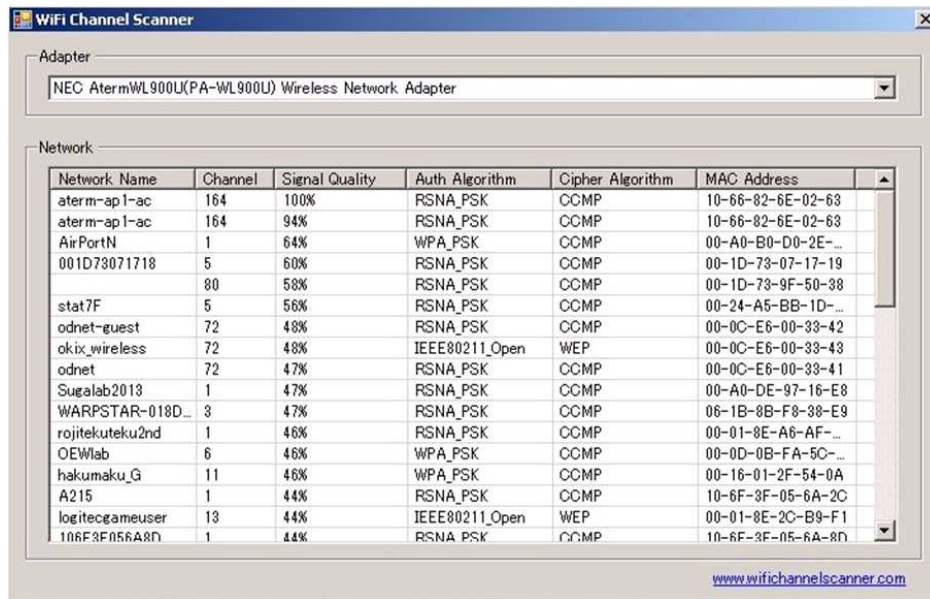
Figure 3.22: Observed WiFi networks by Wi-Fi Channel Scanner in Windows 7.
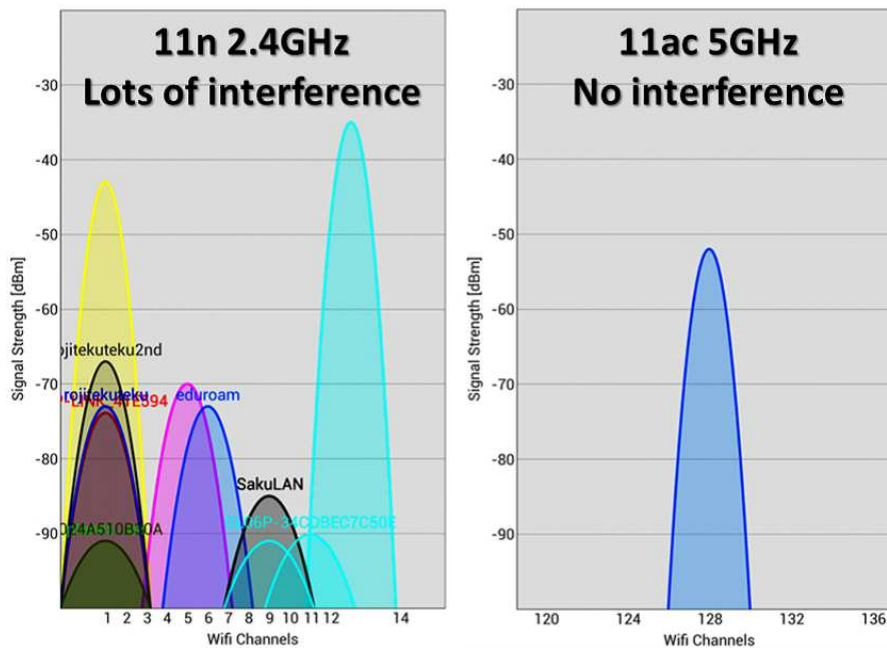
Figure 3.23: Observed 2.4 GHz and 5 GHz WiFi networks by Wifi Analyzer.

Combining the channel scanning results, we selected the least interfered WiFi channel at the test site. If no suitable channel was available during the measurement experiment, we conducted tests during off peak hour, such as midnight, weekend or holiday time, as these hours has the least number of users using WiFi, resulting in less interference and much accurate results towards our measurements.

3.1.3.6 Thermal Fade Interference

Thermal fade effect is a type of natural interference towards the wireless signal due to temperature and relative humidity (RH) factor [51]. From [52] and [53], we had found out that these two factors has affected the intensity level of our WiFi signals at 2.4 GHz and 5 GHz. By referring to meteorological data provided by [54], this effect is very obvious, especially during hot summer time in Okayama due to higher RH percentage. The investigation done by [49] also shows that high humidity tendencies absorb some WiFi signals and cause high changes in the received throughput.

During the throughput test, we measured these values with RH meter and found out that higher RH value degrades the performance of WiFi throughput. Table 3.1 shows comparisons among different RH values during two of our indoor tests (tested with IEEE 802.11ac 5 GHz using Buffalo USB WiFi & AP). In order to gain better and accurate throughput rates, tests should be conducted during lower RH rate. Outdoor measurements done by [55] also show that temperature, atmospheric pressure, and humidity are weather conditions with the highest impact on 2.4 GHz IEEE802.11b/g. Further research regarding this interference is required to prove its effectiveness towards WiFi signal.

Table 3.1: Thermal fade effects towards IEEE 802.11ac host to AP WiFi throughput.

Test	Date	Time	°C	RH	Throughput
a	04 Jul'14	14.51	27°C	74%	$214Mbps$
	30 Jul'14	12.59	34°C	51%	$449Mbps$
b	12 Aug'14	11.00	29°C	56%	$60Mbps$
	28 Aug'14	11.30	29°C	42%	$126Mbps$

3.1.3.7 iperf

In our experiments, we used *iperf v2.0.5* in Figure 3.24 as a software tool to measure the TCP throughput. Iperf can accurately provide the detailed communication performance by setting the parameters in the software properly [56]. The default command for the server is *iperf -s*, and that for the client is *iperf -c 192.168.2.102 -t 50 -i 10*.

During the throughput test, we had a total of nine hosts (clients in iperf) using IEEE 802.11ac or IEEE 802.11n WiFi connects to the AP (a server in iperf). In order to run the whole test in an efficient and accurate way, both server and hosts have been configured with batch files in Figure 3.25. The server is executed with current date and time shown in two lines on the screen using the command "*date /t and time /t*". Next, the iperf server command "*iperf -s -w 477K -l 8K*" is executed with the TCP optimum window size of $477KB$ and the default buffer length of $8KB$. With the maximum network bandwidth of $1300Mbps$ for IEEE 802.11ac and network delay of $3ms$, this optimum window size can be calculated with Eq. (3.1) using "SG Bandwidth*Delay Product Calculator" from Speed Guide, Inc.

$$Windows\ Size = Network\ Bandwidth \times Delay \tag{3.1}$$

At the client side, two batch files are required during the throughput test. The first batch file "54.bat" runs the iperf client command "*iperf -c 192.168.11.54 -t 50 -i 10 -w 477K -l 8K*" for a duration of 50 seconds "*-t 50*" and displays the throughput info for every 10

```
C:\iperf>iperf.exe -s
------------------------------------------------------------
Server listening on TCP port 5001
TCP window size: 21.0 KByte (default)
------------------------------------------------------------
[  4] local 192.168.2.102 port 5001 connected with
192.168.2.103 port 36131
[ ID] Interval       Transfer     Bandwidth
[  4] 0.0-50.1 sec  1.03 GBytes   177 Mbits/sec
```
Server's operation

```
C:\iperf>iperf.exe -c 192.168.2.102 -t 50 -i 10
------------------------------------------------------------
Client connecting to 192.168.2.102, TCP port 5001
TCP window size: 21.0 KByte (default)
------------------------------------------------------------
[  3] local 192.168.2.103 port 38514 connected with
192.168.2.102 port 5001
[ ID] Interval       Transfer     Bandwidth
[  3] 0.0-50.0 sec  4.36 GBytes   750 Mbits/sec
```
Client's operation

Figure 3.24: Operation of iperf software for server and client.

```
date /t
time /t
iperf -s -w 477K -l 8K
```
Server's operation: Server.bat

```
echo Start of 9 Hosts Test & date /t & time /t
iperf -c 192.168.11.54 -t 50 -i 10 -w 477K -l 8K
echo End of 9 Hosts Test & time /t
```
Client's operation: 54.bat

```
timeout 30
54.bat >> 51-54-T7_140530.txt
```
Client's operation: 51-54-T7.bat

Figure 3.25: Contain of batch file for both server and client.

seconds "*-i 10*". At the host side, the same TCP optimum window size of 477 KB and buffer length of 8 KB with using "*-w 477K -l 8K*" are used.

The "*echo Start of 9 Hosts Test & date /t & time /t*" and "*echo End of 9 Hosts Test & time /t*" commands informs the user about the starting and ending of throughput test. As for the second batch file "51-54-T7.bat", after 30 seconds of delay using "*timeout 30*" command, it executes the batch file "54.bat" again and saves the whole process into a text file named "51-54-T7_140530.txt" with the command "*54.bat >> 51-54-T7_140530.txt*". As a result, all test results for every host are automatically saved in a text file to ease the work of data sorting later.

3.2   Measurement Results

By combining the optimization methods as well as interference detection in the previous section, we present throughput measurement results and discussions of the following cases.

3.2.1   Throughput Comparison between Indoor and Outdoor

We had done the throughput comparison of links connecting two APs between indoor and outdoor sites. Figure 3.26 shows the results for IEEE 802.11ac using Buffalo WZR-G1750DHP and those for IEEE 802.11n using Buffalo WZR- G302H. They indicate that for IEEE 802.11ac, indoor sites provide higher throughputs than outdoor sites, and throughputs are gradually decreased as the longer distance. This is due to indoor closed area by walls that act as waveguides [50] which are much more suitable for waveform reflecting and MIMO-OFDM modulation of IEEE 802.11ac compared with open space area at outdoor [57, 58].
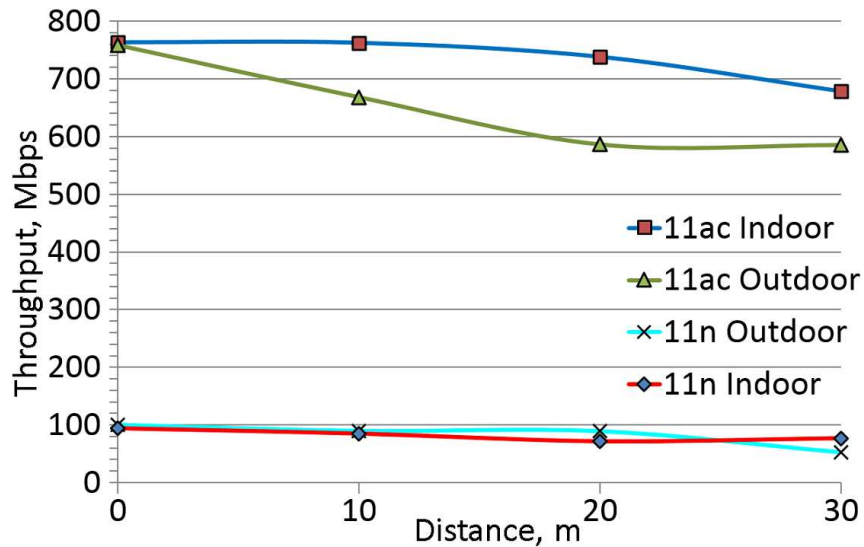
Figure 3.26: IEEE 802.11ac/11n AP to AP throughput comparisons between indoor and outdoor using Buffalo WZR-G1750DHP and Buffalo WZR- G302H.

On the other hand, for IEEE 802.11n, outdoor sites provide higher throughputs than indoor sites until $20m$ distance. At a distance of $30m$, the indoor throughput increased due to multipath propagation effect [59, 60]. Throughputs by IEEE 802.11ac is about eight times of that by IEEE 802.11n due to new technologies introduced with IEEE 802.11ac as follows [12, 49, 61, 62]:

- Extended MIMO operations which support for up to eight spatial streams (versus four in IEEE 802.11n).

- 80 MHz channel bandwidth instead of 40 MHz, which has doubled the size of the spectral channel over IEEE 802.11n.

- Downlink MU-MIMO, allows up to four simultaneous downlink MU-MIMO hosts.

- 256 Quadrature Amplitude Modulation (QAM), added as optional modes (versus 64 QAM, rate 5/6 maximum in IEEE 802.11n).

- Beamforming transmission with explicit feedback (non-standard in IEEE 802.11n).

In another mode, we did the throughput comparison between the same indoor and outdoor sites under host (USB WiFi) to AP mode. Figure 3.27 shows the results for IEEE 802.11ac using Buffalo WZR-G1750DHP and its respective USB WiFi adapter. It is obvious that in the closed area, walls serve as good reflectors for WiFi signal at indoor compared with outdoor open space area. As a result, the indoor results are about double the throughput of outdoor test results.
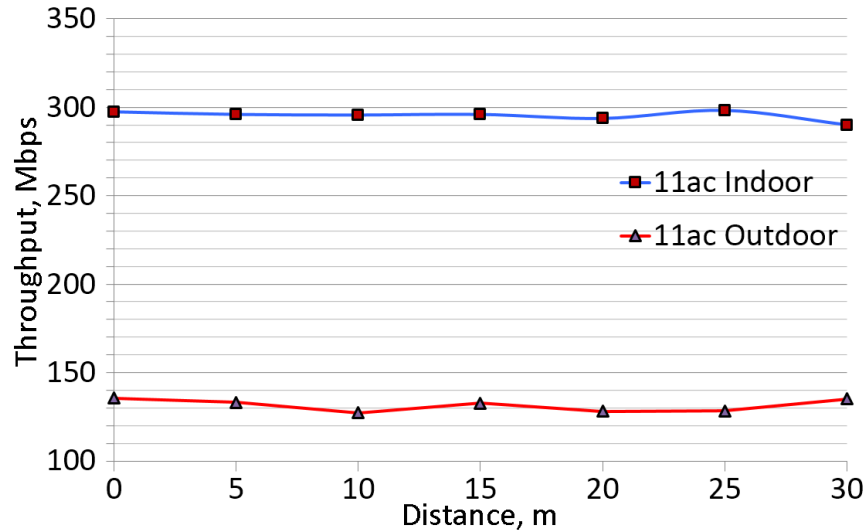
Figure 3.27: IEEE 802.11ac Host to AP throughput comparisons between indoor and outdoor using Buffalo WZR-G1750DHP

3.2.2 Throughput Comparison between One-hop and Two-hop Communications

We compared the throughput between one-hop and two-hop communications for the topology in Figure 3.3 and Figure 3.4.

Figure 3.28 shows the results for IEEE 802.11ac using Buffalo WZR-G1750DHP and those for IEEE 802.11n using Buffalo WZR-G302H. In these tests, on average, the throughputs of two-hop communications become about half of these of one-hop communications for IEEE 802.11n. While for IEEE 802.11ac, the throughputs reduce about 62% on average from one-hop to two-hop. On overall, both IEEE 802.11ac and IEEE 802.11n WiFi are still able to maintain good throughputs even at a distance of $30m$ due to surrounding walls at indoor.

According to [63–65], one hop will reduce the throughputs by 50% and this has been proven for both types of WiFi.

3.2.3 Throughput Change by Wall

In this part, we evaluated throughput changes due to wall obstacles along the link path under various conditions.
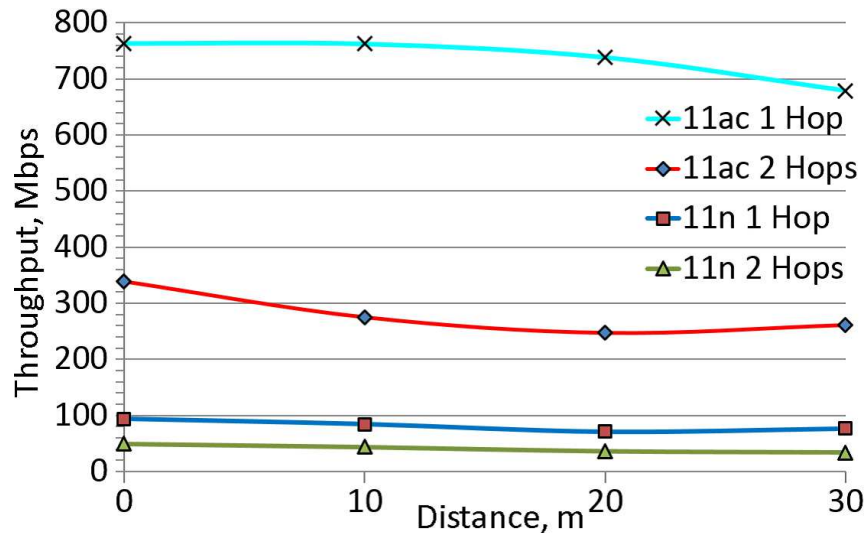
Figure 3.28: IEEE 802.11ac/11n throughput comparisons between one-hop and two-hop communications

3.2.3.1 Effects of Wall Towards Usage of Repeater

We evaluated the throughput's changes by using a repeater between the end nodes. Figure 3.29 compares the throughputs with and without a repeater for the topology in Figure 3.5. The results show that using the repeater, the throughput by Buffalo WZR-G1750DHP IEEE 802.11ac increased by 7% and the throughput by Buffalo WZR-HP-G302H IEEE 802.11n increased by 540%. Thus, the effect of the repeater is confirmed.
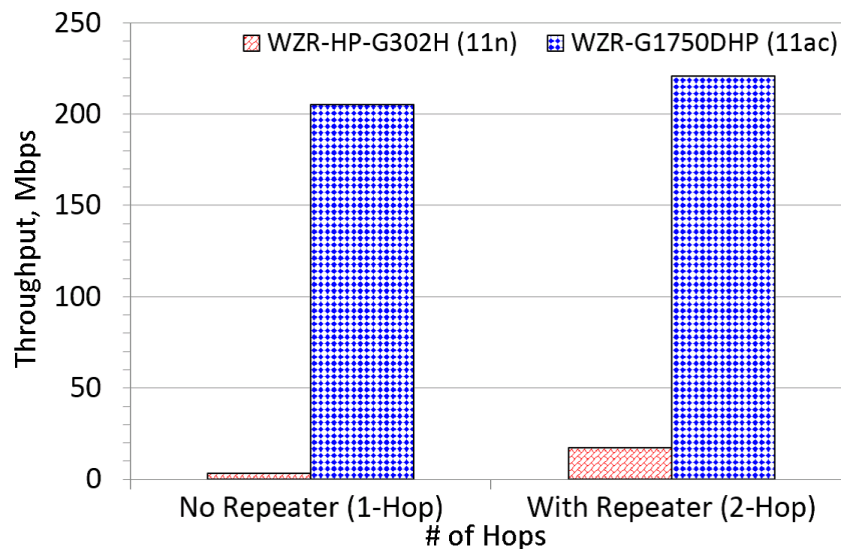
Figure 3.29: Effect of repeater in indoor with two walls.

3.2.3.2 Effects of Wall Towards IEEE 802.11ac with Various Vendor

We tested the variable obstacles with concrete walls using Buffalo WZR-1750DHP, I-O Data Air Port WN-AC1600DGR, and NEC Aterm WG1800HP AP to evaluate the effects of wall

obstacles towards IEEE 802.11ac 5 GHz WiFi signal. Noted that the AP from I-O Data does not allow the repeater use in IEEE 802.11ac.

Figure 3.30 shows the effects of wall obstacle towards IEEE 802.11ac throughput from host (USB WiFi) to AP and AP to AP using different vendors. In the host to AP, Buffalo performs better than others under the test condition of no wall and one wall. For two wall test condition, NEC outperforms other vendors at least 27%.
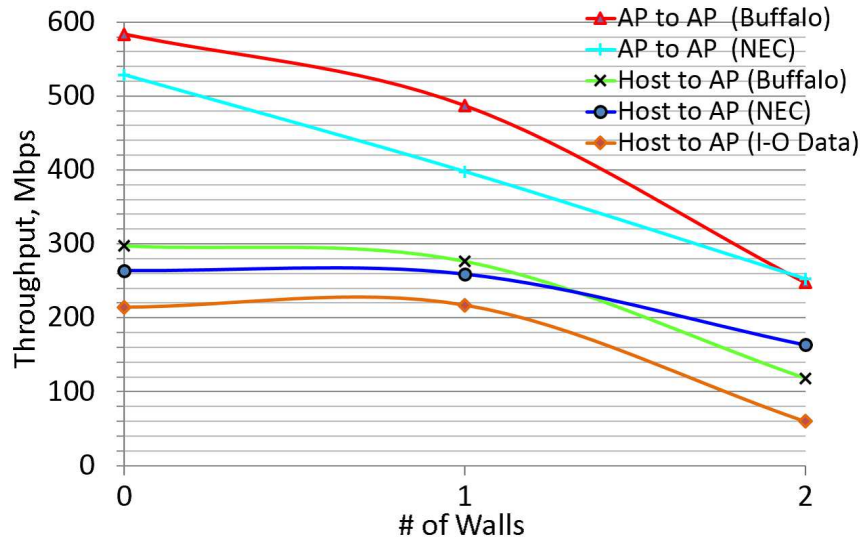
Figure 3.30: Effects of wall obstacle towards IEEE 802.11ac throughput from host to AP and AP to AP using different vendor.

The maximum throughput for IEEE 802.11ac USB WiFi to AP at $8m$ distance is about $291Mbps$. Under this no wall condition, the host reached its top speed. For the AP to AP, the average drop around 32% was obtained per wall obstacle. The AP to AP's throughput is about double the host to AP mode performance.

3.2.3.3   Effects of Wall Towards IEEE 802.11n with Various Vendor

We repeated the test using the same devices with IEEE 802.11n configuration to evaluate the effects of wall obstacles towards IEEE 802.11n WiFi signal. Noted that the AP from I-O Data does not allow the repeater in IEEE 802.11n.

Figure 3.31 shows the effects of wall obstacle towards IEEE 802.11n throughput from host to AP using different vendors. I-O Data AP provides the best throughput under no wall and one wall conditions. Both the Buffalo WZR-1750DHP and NEC Aterm WG1800HP AP are newer and better than the older Buffalo WZR-HP-G302H, they still have similar throughput results under all conditions. This is because the host reached its maximum speed. The throughput is fully dependent on the build-in WiFi model on the host side.

Figure 3.32 shows the effects of wall obstacle towards IEEE 802.11n throughput from AP to AP using different vendors. The newer Buffalo WZR-1750DHP AP has the best throughput among the three models of APs. It can provide the similar throughput under both no wall and one wall condition. Both NEC and Buffalo WZR-HP-G302H AP had linear throughput results as numbers of wall increased. The older Buffalo WZR-HP-G302H IEEE 802.11n AP had the lower throughput due to its older hardware technology.
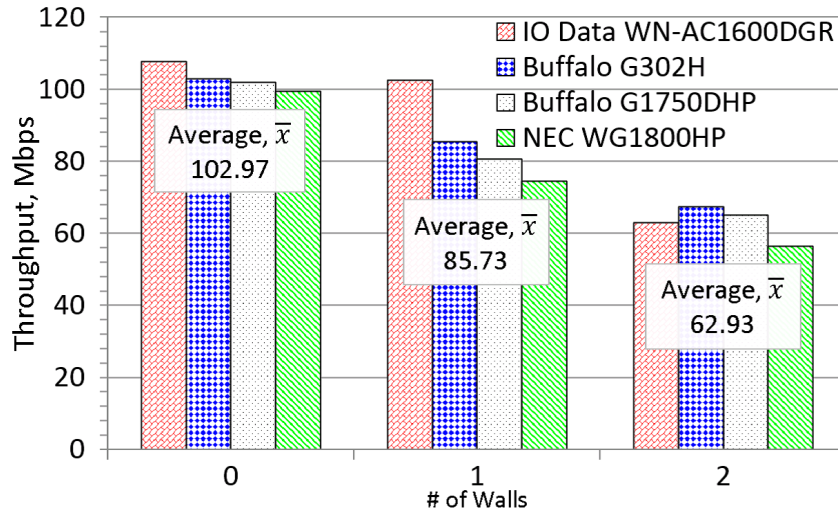
Figure 3.31: Effects of wall obstacle towards IEEE 802.11n throughput from host to AP using different vendor.
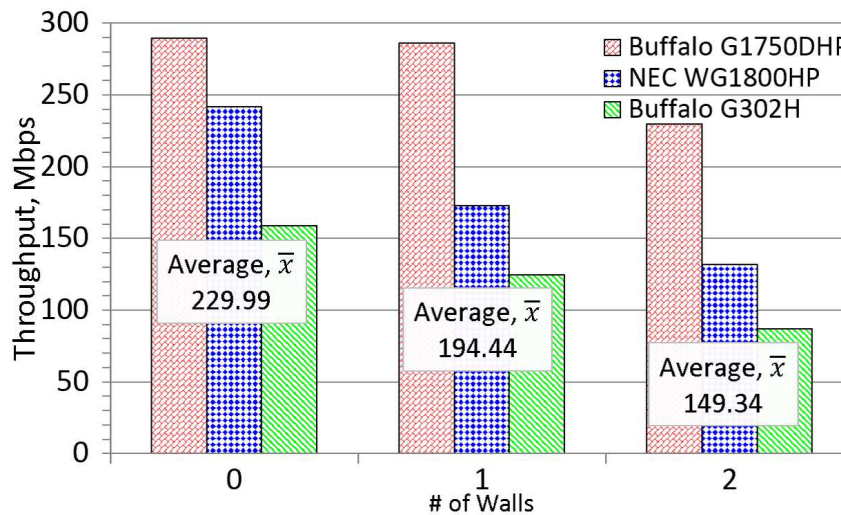
Figure 3.32: Effects of wall obstacle towards IEEE 802.11n throughput from AP to AP using different vendor.

3.2.3.4   Effects of Wall Towards IEEE 802.11ac/11n with Link Distance Change

In the lecture hall site, we had the throughput measurements with the assumption that the AP located inside the hall. Figure 3.33 shows the effects of one wall obstacle towards IEEE 802.11ac/11n using Buffalo WZR-1750DHP.

In the host to AP communication, the throughput of IEEE 802.11ac was at least 75% faster than IEEE 802.11n, with minimum speed of $82Mbps$. For the AP to AP communication, which simulates the usage of the repeater, the throughput of IEEE 802.11ac was at least 50% faster than IEEE 802.11n, with minimum speed of $166Mbps$ even at $30m$ distance. For IEEE 802.11n AP to AP communication, the throughput was more than 56% faster than host to AP mode with minimum speed of $74Mbps$. The throughput of IEEE 802.11n at a distance of $30m$ become better due to multipath effects.
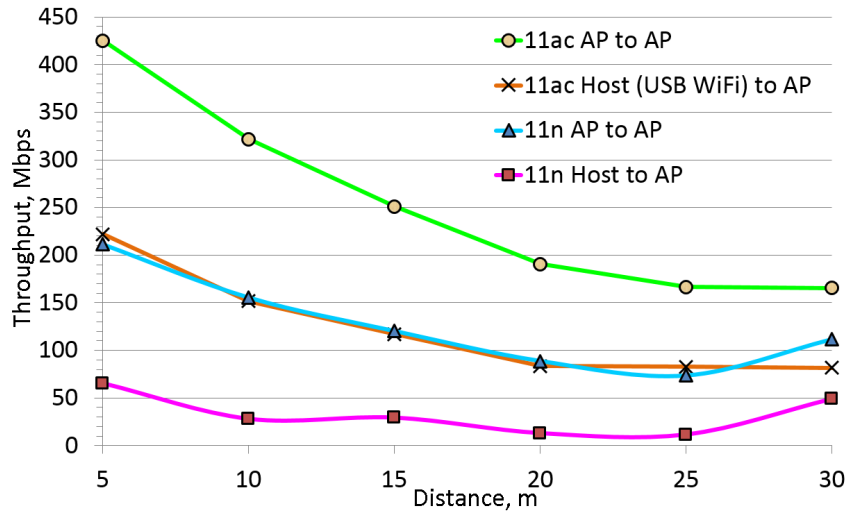
Figure 3.33: Effects of one wall obstacle towards IEEE 802.11ac/11n with link distance change.

3.2.4 Throughput Change by Repeater

We evaluated throughput improvements by adopting one IEEE 802.11ac repeater between the server and two hosts when a wall obstacle separates them as in Figure 3.9. The devices from the three vendors are used, where those from I-O Data do not allow the repeater use (only one hop communications). For IEEE 802.11n devices at hosts, both of the external USB WiFi device and the build-in device in the host PC are evaluated.

Table 3.2 shows the throughput measurement results. The results indicate:

1. NEC devices provide the highest throughput for one-hop communications, and for two-hop communications using the external USB WiFi device.

2. Buffalo devices provide the highest throughput when build-in devices in PCs use with the IEEE 802.11ac repeater, which can be the most conventional.

3. The adoption of an IEEE 802.11ac repeater improves the throughput for any case.

Table 3.2: Effects of IEEE 802.11ac repeater in indoor with one wall using devices from three vendors.

Vendor	Throughput ($Mbps$)			
	USB WiFi		Build-in WiFi	
Repeater	No	Yes	No	Yes
Buffalo	107.28	128.6	73.37	97.25
I-O Data	138.53	-	79.47	-
NEC	194.83	199.8	85.42	93.33

3.2.5 Throughput Comparison between 2.4 GHz and 5 GHz

We evaluated the difference between the 2.4 GHz's IEEE 802.11n and 5 GHz's IEEE 802.11ac under variable obstacles from no wall to two walls with various vendor.

The overall average throughput of 5 GHz IEEE 802.11ac in host to AP and AP to AP, and 2.4 GHz IEEE 802.11n host to AP and AP to AP can be summarized as in Figure 3.34. The throughput of 5 GHz IEEE 802.11ac, in both host to AP and AP to AP mode, drops by 55% when the number of walls increase from zero to two. While the throughput of 2.4 GHz IEEE 802.11n, drops by 35% only when the number of walls increase from zero to two. In all cases, the throughput of AP-AP mode is about double the throughput of host to AP mode, as AP-AP mode having more antennas in the AP compared host.
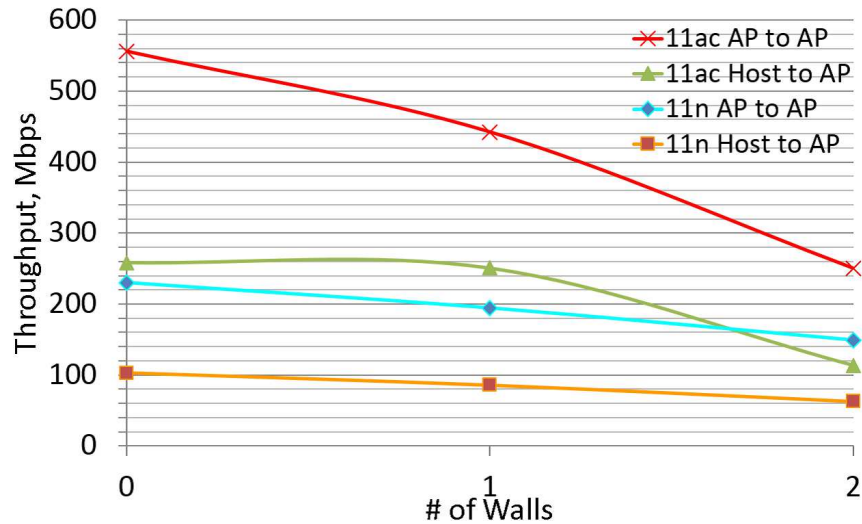
Figure 3.34: Effects of wall obstacles towards 5GHz IEEE 802.11ac and 2.4GHz IEEE 802.11n.

Table 3.3 and Table 3.4 show the throughput comparison between the 2.4 GHz and 5 GHz from no wall to two walls, for both host to AP and AP to AP. It was obvious that the 5 GHz IEEE 802.11ac tends to have a higher percentage of throughput drop, which was at least 55% compared with the 2.4 GHz frequency. This indicated that it has a shorter transmission range under wall obstacles condition. In both cases, the 2.4 GHz had a reduction of at most 39% as it has a wider radio wave length if compared with 5 GHz.

Table 3.3: Effects of different WiFi frequency towards throughput from host to AP.

	2.4 GHz	5 GHz
No Wall	$103Mbps$	$258Mbps$
2 Walls	$63Mbps$	$114Mbps$
% of Reduction	39%	56%

Table 3.4: Effects of different WiFi frequency towards throughput from AP to AP.

	2.4 GHz	5 GHz
No Wall	$230Mbps$	$556Mbps$
2 Walls	$149Mbps$	$250Mbps$
% of Reduction	35%	55%

3.2.6 Throughput Comparison among Different AP Locations

In this section, we used IEEE 802.11ac USB WiFi devices and build-in IEEE 802.11n WiFi devices in the notebook PCs to compare throughputs for the different number of Buffalo WZR-1750DHP APs, the different number of hosts as well as the different locations in a large lecture hall in our campus. Two types of cases are evaluated, which are the ideal case and practical case as explained in details at Section 3.1.1.2.

3.2.6.1 IEEE 802.11ac's Ideal Case

Figure 3.35 shows the throughput results for IEEE 802.11ac using one and two APs. For nine hosts in both one and two APs, the throughput suddenly goes up because host 9 is nearer to its associated AP. From this figure, we can see that two APs (simulated as GWs) using different channels, located at ideal positions, can double the throughput (average range from 90%-114%) of one AP as an additional AP provides twice the bandwidth to all hosts [66].
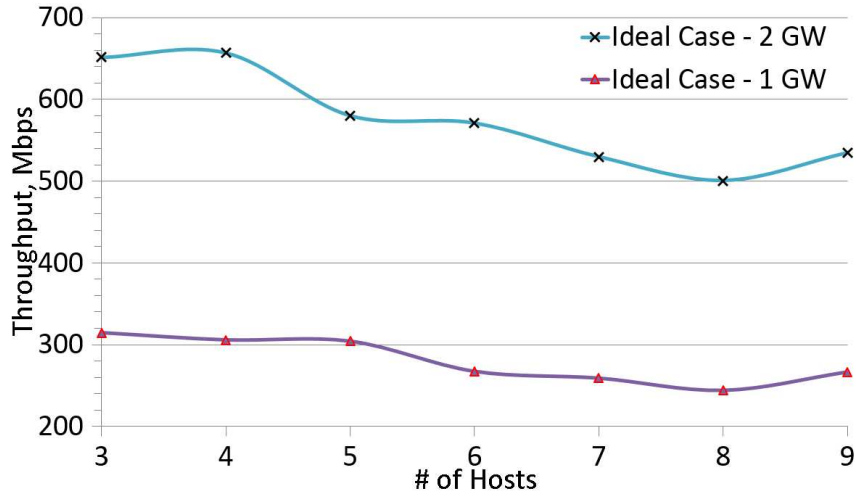
Figure 3.35: IEEE 802.11ac throughput comparison between one AP and two APs for ideal AP locations.

3.2.6.2 IEEE 802.11ac's Practical Case

Figure 3.36 shows the throughput results when the number of IEEE 802.11ac's APs is changed from one to three. Two provide an increase of throughput for at least 47% over one AP. While three APs are 114% faster than one AP and 23% faster than two APs. The throughput increases with the number of APs. However, for two-AP cases, the throughput decreases tremendously when seven or more hosts join. The reason may come from the WiFi interference increase, whose analysis will be in our future works.

Figure 3.37 shows the comparison of the IEEE 802.11ac throughputs between ideal and practical AP locations. For one AP throughput, the ideal case is better than the practical case for three to five hosts position and they make the difference between both ideal and practical cases. After five hosts, the AP position does not improve the performance. For two APs, the ideal case is better than the practical case due to the short distance between hosts and GWs. In overall, they show that throughputs are greatly affected by AP locations for two-AP cases and are not affected for one-AP cases.
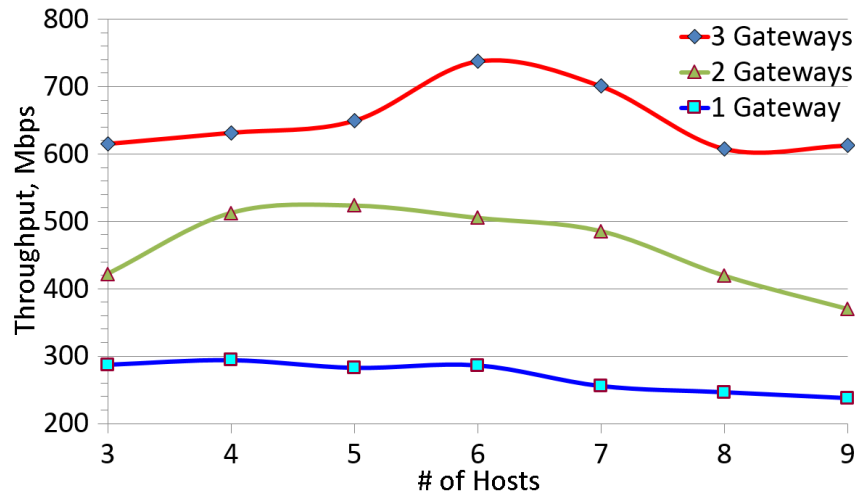
Figure 3.36: IEEE 802.11ac throughputs with one to three APs for practical AP location.
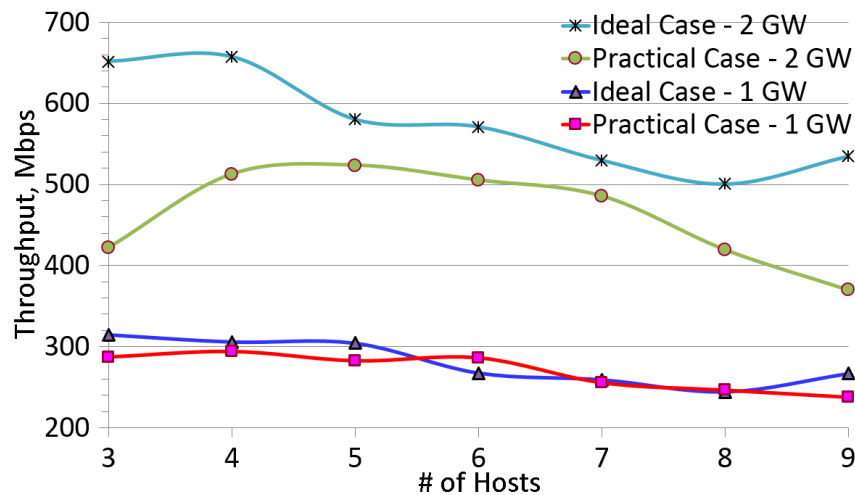
Figure 3.37: IEEE 802.11ac throughputs comparison between ideal and practical AP locations.

3.2.6.3 IEEE 802.11n 5 GHz's Practical Case

Figure 3.38 shows the IEEE 802.11n 5 GHz throughput results when the number of IEEE 802.11n's APs (simulated as GWs) is changed from one to three. The throughput results of IEEE 802.11n 5 GHz tests were similar to the IEEE 802.11ac's practical case in the previous section. Both of them have throughput increases with the number of APs. In this wireless network, two APs improve the throughput of one AP for at least 51.4%. While the usage of three APs improve the throughput over 31.6% and 121% compared with two APs and one AP.

3.2.6.4 IEEE 802.11n 2.4 GHz's Practical Case

Figure 3.39 shows the IEEE 802.11n 2.4 GHz band 40 MHz bandwidth throughput results when the number of IEEE 802.11n's APs is changed from one to three. The throughput decreases with the number of APs. For two APs case, interference occurs during seven to eight hosts test. As a result, throughput drops a lot. In this practical case, as IEEE 802.11n
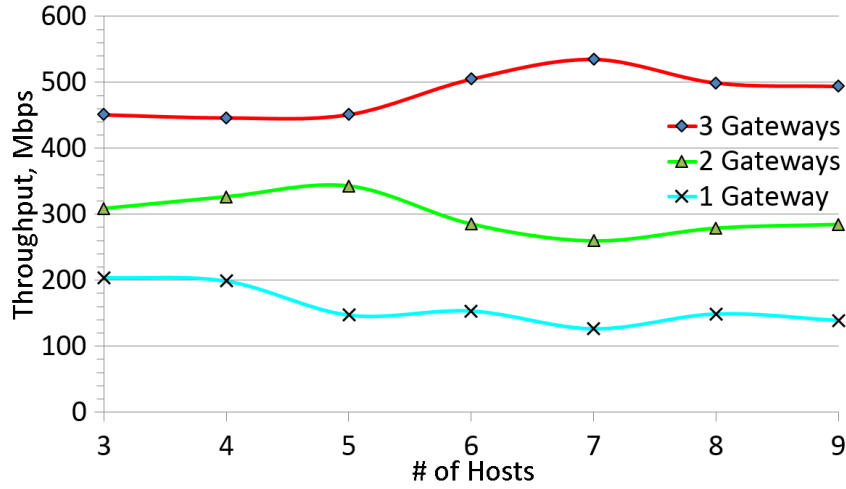
Figure 3.38: Effects of variable APs towards IEEE 802.11n 5 GHz throughput in practical case.

2.4 GHz has limited channels and bandwidth, the throughput has dropped tremendously (range from $34 - 50\%$) in three APs due to overlapping of the channels.
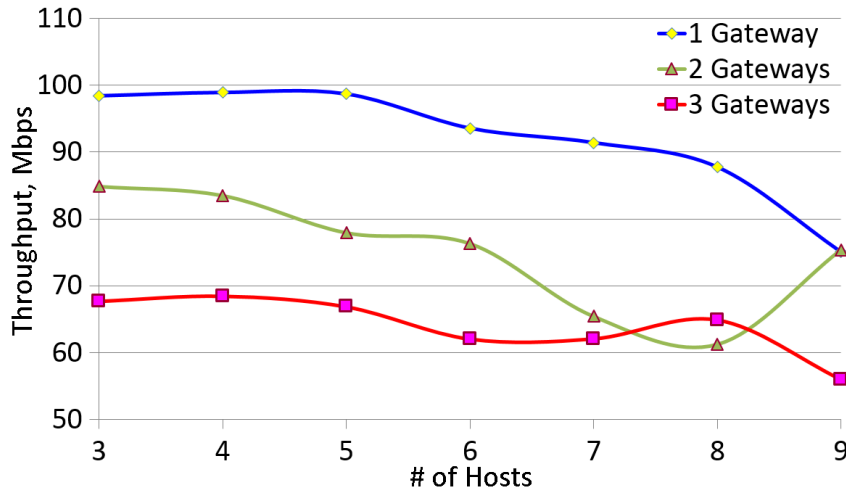
Figure 3.39: Effects of variable APs towards IEEE 802.11n 2.4 GHz throughput in practical case.

3.2.7 Throughput Change by Link Distance

We evaluated throughput changes when the link distance increases under one-hop communications using IEEE 802.11ac and IEEE 802.11n APs from various vendors under different environment.

3.2.7.1 Comparison between IEEE 802.11ac and IEEE 802.11n

Figure 3.40 shows the results for IEEE 802.11ac and IEEE 802.11n when the link distance between APs increases from $0m$ to $100m$ in outdoor sites using Buffalo WZR-G1750DHP

and WZR-HP-G302H. The throughput for IEEE 802.11ac decreases from $758Mbps$ at 0 to $182Mbps$ at $100m$, and that for IEEE 802.11n decreases from $117Mbps$ at $0m$ to $1Mbps$ at $100m$. This means IEEE 802.11ac provides at least six faster throughput of IEEE 802.11n.
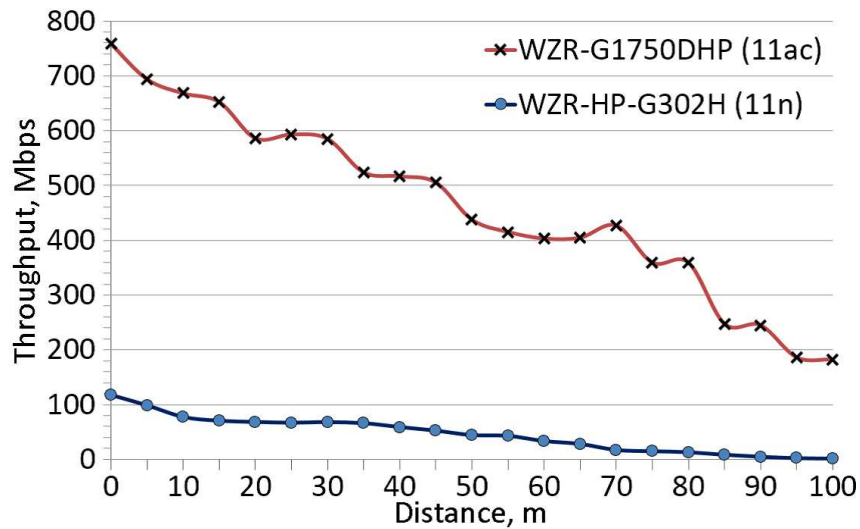
Figure 3.40: IEEE 802.11ac throughput change by increasing link distance at outdoor.

3.2.7.2 Comparison between Vendors

We compared throughputs between different wireless device vendors when the link distance increases in outdoor sites. In each experiment, both IEEE 802.11ac USB WiFi device and AP from the same vendors were used for each test.

Figure 3.41, Figure 3.42, and Figure 3.43 shows throughput changes using devices from Buffalo, I-O Data and NEC respectively. The results by Buffalo and I-O Data similarly decrease as the link distance increases, while the results by NEC are more stable for distance changes.
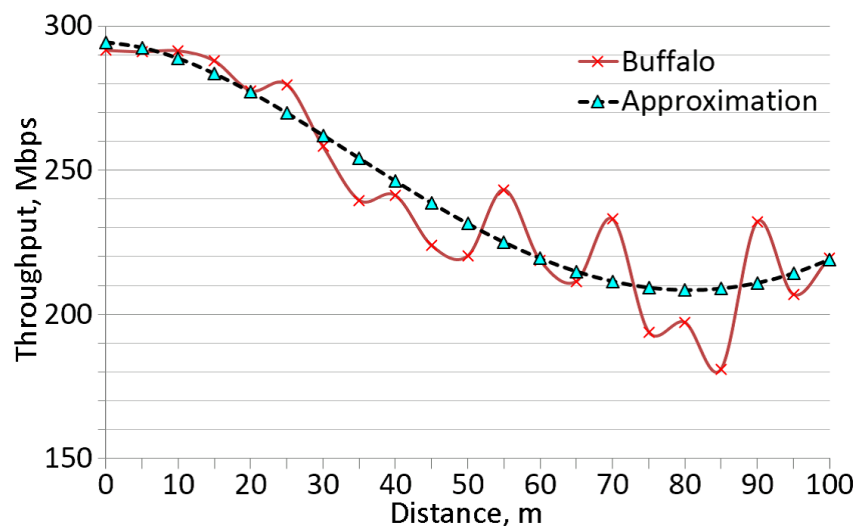
Figure 3.41: IEEE 802.11ac throughput change by increasing link distance in outdoor using Buffalo WZR-G1750DHP & WI-U2-866D USB WiFi.
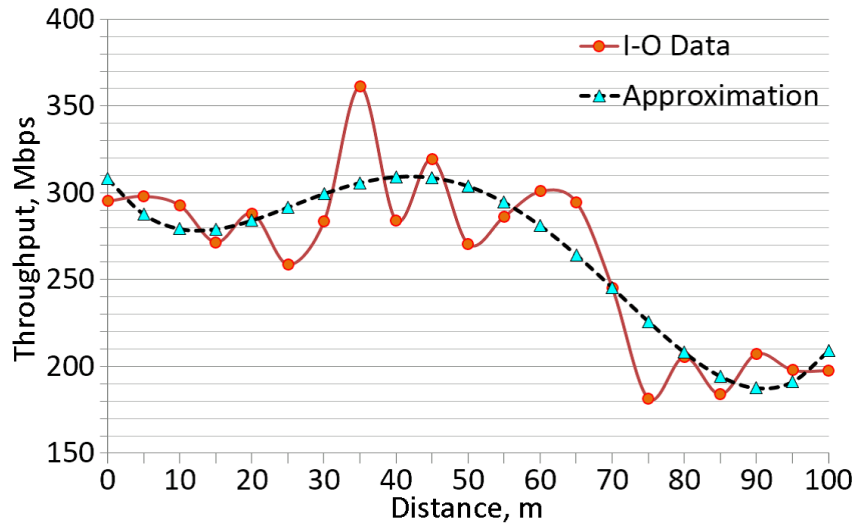
Figure 3.42: IEEE 802.11ac throughput change by increasing link distance in outdoor using I-O Data WN-AC1600DGR & WN-AC867U USB WiFi.
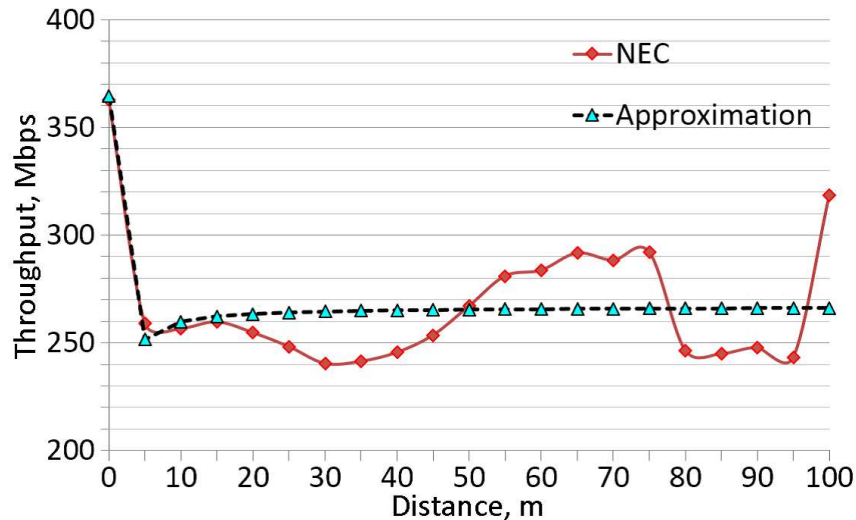
Figure 3.43: IEEE 802.11ac throughput change by increasing link distance in outdoor using NEC WG1800HP & WL900U USB WiFi.

3.2.7.3 Comparison between Open Space and Building

From the tests, we found out that the layout of the experiment area, such as buildings and road junctions around the APs also affected the results. There is a fluctuation of I-O Data at the distance of $35m$. We analyzed the reason of this abnormal phenomena. It is considered that outdoors open space WiFi's signal is free to spread out to anyway. As a result, the power/strength of WiFi decreases with the increase of distance.

Figure 3.44 (source from Google, maps.google.com) shows the position of the host from $0m$ until $100m$ with surrounding high rise buildings and trees. We found out that when the AP located nearby buildings, the throughput becomes better (or worse) as building's walls serve as a WiFi's multi-path condition for waveform reflection. Note that big trees beside the test path also serve as wave reflectors.

According to [50], multi-path WiFi signals take different paths between two points. If

two signals are in the same phase, they interfere constructively and this results in a better throughput; if they are in the different phase, they interfere destructively, and canceling each other out. These constructive and destructive interferences cause lots of changes towards the throughputs at any distance.
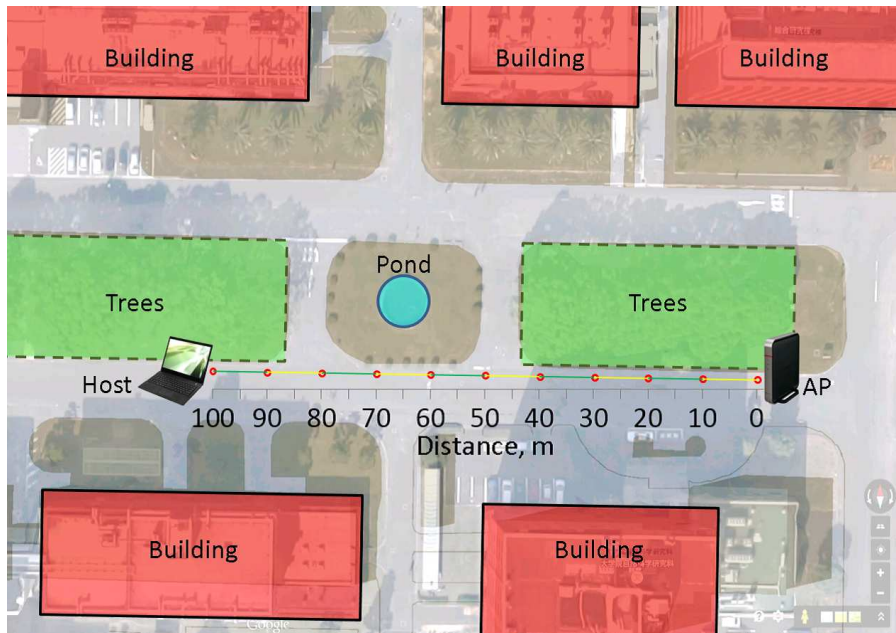
Figure 3.44: Position of host in outdoor tests.

The standard deviations at the positions of $0m$, $35m$, $45m$, $60-75m$, $85m$, and $100m$ are larger values from 35.409 to 68.994, because open space such as road junctions and lots of interference occur around these positions.

As for the rest of the positions, $5-30m$, $40m$, $50-55m$, $80m$ and $90-95m$, the standard deviations range from 17.358 to 25.306. They are far lower because these positions are surrounded by buildings and less interfered by the public WiFi.

All three APs used in the experiment comes in different physical size dimensions. The Buffalo AP has the largest size, I-O Data comes second, and NEC the smallest. The throughput results among different vendors indicate that larger size's AP will provide much stable throughput rate with near linear attenuation as they could have a larger size antenna built into the device at much ideal position. Besides, this large dimension area will provide more spacing among the MIMO antennas and subsequently reduce the interference among them. Smaller APs could not provide stable throughput due to their dimension's limitation that limit the antenna's size.

During the tests, we also found out that the placing angle of AP towards another AP or host also affects the throughput result. All APs have built in antennas where their position are unknown to the user. As a result, the direction of AP facing might affect the result as well. For example, it's impossible to have the antennas located at the back of APs where LAN's ports, Internet's port, and power supply port. If the back side of the AP facing towards another AP/host, the throughput becomes lower compared with the front facing position of APs towards each other.

During the outdoor tests, we found out that placing the AP at position between 30°-45° to the left side or right side facing the host as shown in Figure 3.45 provides the best

throughput. This might be due to WiFi's signal require certain transmission angles to emit signals and reflects against the walls. If the WiFi's signal able to travel through the shortest path (also means shorter time) before reaching the destination, then the throughput would be better than those longer path transmissions that consume longer time. Further research regarding this angle matter is required to prove its effectiveness towards throughputs.
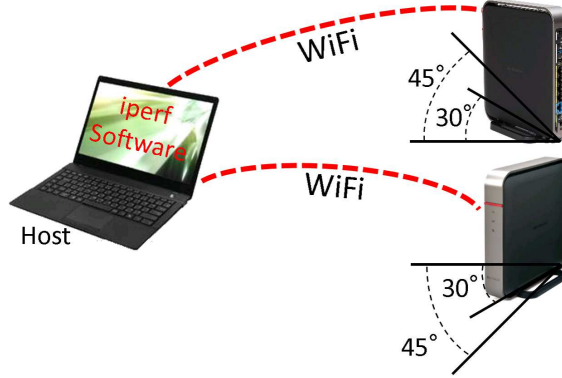
Figure 3.45: Position of AP towards other AP or host(s).

3.3 Throughput Estimation Model

For IEEE 802.11ac, we increase the link distance between APs from 0 to $100m$ at outdoor site. We generated an IEEE 802.11ac AP throughput link distance equation as in Eq. (3.2), with y represent the throughput and x represent the distance from 0 to $100m$.

$$f(x) = -0.0266x^2 - 31.5812x^{\frac{1}{2}} + 762.4162 \tag{3.2}$$

where x represents the link distance (m), and $f(x)$ represents the estimated throughput at distance x $(Mbps)$ from the source AP.

From different wireless device vendor's tests, we combined the throughput results in Figure 3.46 and generated a common IEEE 802.11ac USB WiFi throughput link distance equation as in Eq. (3.3). From Figure 3.46, we can see that the attenuation level of all three IEEE 802.11ac 5 GHz WiFi is far more higher than the IEEE 802.11n 2.4 GHz (as shown in Figure 3.40) due to higher frequency tend to have higher attenuation level and higher throughput drops.

$$u(x) = -0.0025x^2 - 5.6960x^{\frac{1}{2}} + 304.3260 \tag{3.3}$$

where $u(x)$ represents the estimated throughput at distance x $(Mbps)$.

3.4 Discussion

This chapter presented TCP throughput measurements using IEEE 802.11ac/11n devices from three vendors implementing IEEE 802.11ac/11n protocols in various conditions including one or two-hop communications, wall obstacle existences, different link distances, the use of a repeater, and big room with different AP locations. These test conditions show that TCP throughputs are affected by vendors, communication conditions, and AP's location.
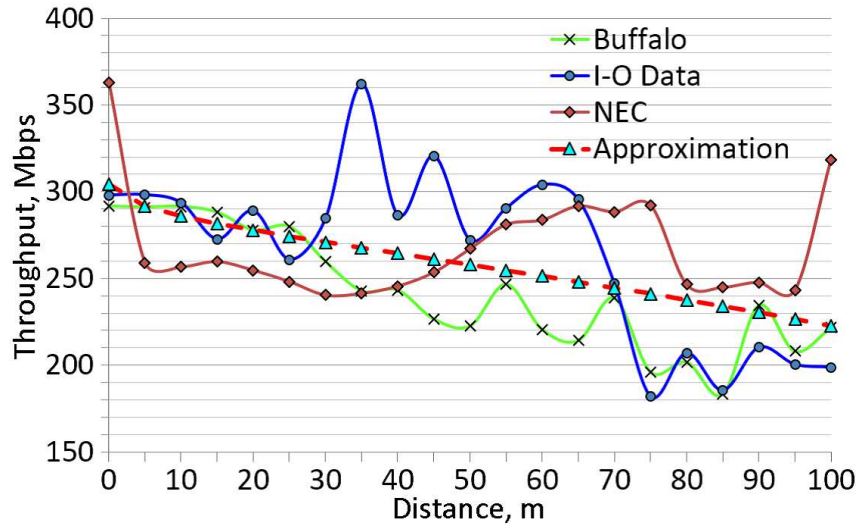
Figure 3.46: Estimated throughput change of IEEE 802.11ac by increasing link distance in outdoor.

By taking into consideration the limitation of indoor/outdoor experiment site's actual physical layout, different weather conditions (due to thermal fade), and wireless network interference, our results from the TCP throughput measurement software *iperf*, indicated that the indoor IEEE 802.11ac provides better throughput than outdoor location, and that IEEE 802.11ac is around eight times faster than IEEE 802.11n.

In the one-hop versus two-hop comparison, our tests show that extra hop will cause both IEEE 802.11ac and IEEE 802.11n throughput drops more than half. While in the wall obstacles, IEEE 802.11n throughput drop rate is larger than IEEE 802.11ac due to the different number of MIMO antennas. The usage of repeater between IEEE 802.11n APs is very effective.

Under the different vendors, Buffalo performs better than I-O Data and NEC under the no wall and one wall conditions. While for two walls, NEC outperforms other vendors. The adoption of an IEEE 802.11ac repeater improves the throughput for the different vendors. Higher frequency WiFi has the largest percentage of throughput's drop.

In the large lecture hall tests, two APs can double the throughput of one AP in the ideal case. While for the practical case, the throughput increases with the number of APs for both IEEE 802.11ac and IEEE 802.11n 5 GHz cases. As for the IEEE 802.11n 2.4 GHz practical case, the throughput decreases with the number of APs.

For the last part, we can assume that the antenna's size is limited by the physical dimension of AP. Outdoor buildings or geographical layout affects the throughput of IEEE 802.11ac. The standard deviation analysis shows that interference occurs at nine positions.

We generated a common link distance equation for IEEE 802.11ac by combining throughput test results from three vendors and use for the active AP selection algorithm in WIMNET in the following chapters.

Chapter 4

Extended Routing Algorithm

In this chapter, we present the extended routing algorithm for WIMNET to consider the link speed change.

4.1 Problem Formulation

The extended routing path problem can be defined as follows:

1. Input

   (a) Network topology: $G = (V, E)$
      - set of nodes (APs, hosts): V
      - each node type: GW, AP, or host
      - each node coordinate: (x, y)
      - number of nodes: $N(= |V|)$
      - set of links between nodes: E
         - link speed for link k: s_k

   (b) Minimum link speed for routing path: S_{route}

2. Output

   Routing path: T

3. Constraint

   (a) Any host must be connected with GW in T (host covering constraint).

   (b) For each node, either of the following nodes must be selected for the downstream connection (node type connection constraint):
      - AP: AP or host
      - host: no node

4. Objective

The cost function E representing the maximum propagation and transmission delays in the routing path should be minimized:

$$E = \alpha \cdot \max_{i \in V} \left[\sum_{k \in P_i} \frac{1}{s_k} \right] + \beta \cdot \left(\max_{k \in N_{GW}} \left[\frac{t_k}{s_k} \right] - \min_{k \in N_{GW}} \left[\frac{t_k}{s_k} \right] \right) \qquad (4.1)$$

where α and β represent constant coefficients for the both delays respectively, t_k does the number of hosts using link k, P_i does the set of nodes in the routing path between the GW and node i, and N_{GW} does the set of incident links to the GW.

4.2 Throughput Estimation

In this section, we briefly review our throughput estimation using commercial products.

4.2.1 IEEE 802.11n/g

In our measurements for IEEE 802.11n/g, we prepared two PCs that are equipped with the IEEE 802.11n/g NICs and the necessary software. We measured the throughput while increasing the distance between them with the $5m$ interval. Table 4.1 shows the devices and software for measurements.

Table 4.1: Devices and software for throughput measurement.

	Type	UNITCOM W760C
	CPU	core i3 370M (2.40 GHz)
	Memory	2 GB
PC	OS	Ubuntu11.10
	NIC	Buffalo WLI-UC-G300HP
	Software	iperf2.0.5
	Protocol	TCP
AP	Type	Buffalo WZR-HP-G302H

Figure 4.1 shows changes of measured throughput when the link distance is increased from $0m$ to $100m$ for IEEE 802.11n. To estimate the link speed from the distance using the results, we approximated the throughput change by the third-order linear equation as follows:

$$n(x) = \begin{cases} -0.0022x^3 + 0.1853x^2 - 5.3348x + 117.43 & (0 \leq x < 40) \\ -0.00006x^3 + 0.0095x^2 - 1.732x + 117.17 & (40 \leq x < 75) \\ 0.000438x^3 - 0.10955x^2 + 8.477156x - 189.48 & (75 \leq x < 100) \\ 1 & (100 \leq x) \end{cases} \qquad (4.2)$$

where $n(x)$ represents the estimated throughput at distance x ($Mbps$).

The estimation result using this equation is plotted by the dot-line in this figure. The coincidence between two lines confirms the accuracy of this estimation.
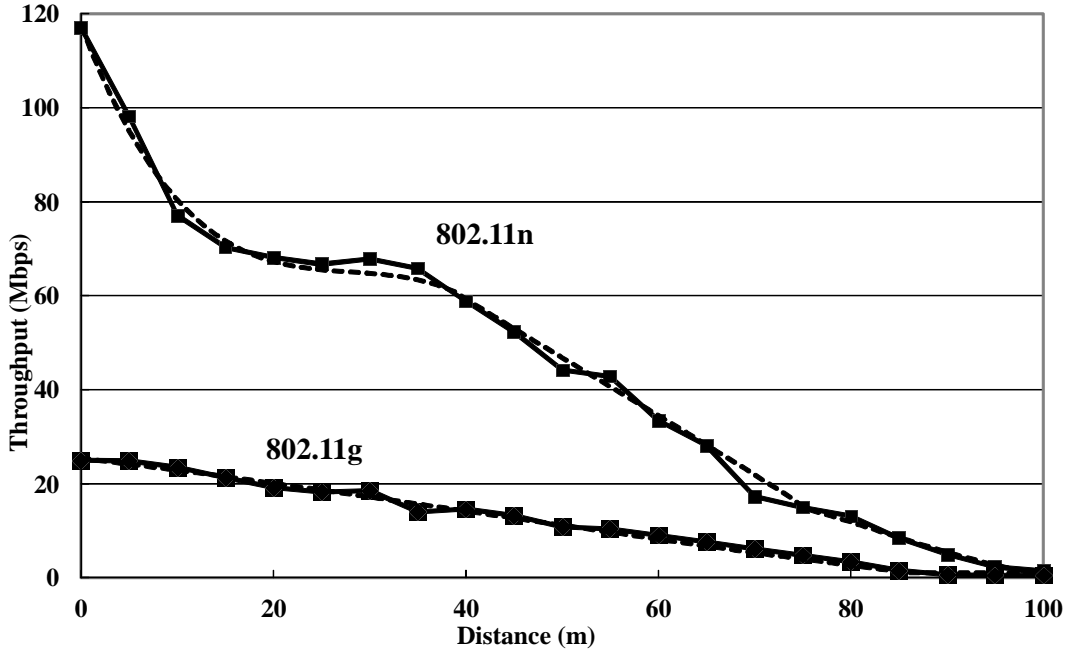
Figure 4.1: Throughput measurement and estimation result.

Additionally, we measured the throughput changes when the IEEE 802.11g protocol was used at the same NICs for comparisons. This result is also depicted in Figure 4.1 with the estimation result by the following equation:

$$g(x) = \begin{cases} 0.00001x^3 - 0.0013x^2 - 0.2454x + 25.424 & (0 \le x < 85) \\ 1 & (85 \le x) \end{cases} \tag{4.3}$$

where $g(x)$ represents the estimated throughput at distance x (*Mbps*).

4.2.2 IEEE 802.11ac

In our measurements for IEEE 802.11ac, we prepared two PCs that are equipped with the IEEE 802.11ac NICs and the necessary software. We measured the throughput while increasing the distance between them with the $5m$ interval. Table 4.2 shows the devices and software for measurements.

Figure 3.40 from Section3.2.7.1 shows the changes of measured throughputs when the link distance is increased from $0m$ to $100m$ with the $5m$ interval for IEEE 802.11ac. To use the measurement results in the routing algorithm and the WIMNET simulator for the throughput estimation, we approximate the throughput change by the third-order linear equation as $f(x)$ in Eq. (3.2) in Section3.3

In this dissertation, we recommend that the link speed is measured using wireless devices in a real network field. However, at the network design phase where the real field does not exist like simulations in this dissertation, or when sufficient devices for measurements are not available, it cannot. In such a case, we estimate the link speed using $f(x)$ in (3.2) and

Table 4.2: Devices and software for throughput measurement.

PC1	Model	Ultrabook Lesance NB S3441/L
	CPU	Intel (R) Core i5 3317U (2.6 GHz)
	OS	Windows7
PC2	Model	Ultrabook Lesance NB S3532-SP
	CPU	Intel (R) Core i3 2350M (2.3 GHz)
	OS	Windows7
AP		Buffalo WZR-G1750DHP
Software		iperf2.0.5
Protocol		TCP

$n(x)$ in (4.2) with the given locations of the nodes. The link speed s_k between node i and node j is estimated using the Euclid distance by:

$$s_k = f\left(\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\right) \tag{4.4}$$

where (x_i, y_i) and (x_j, y_j) represent the location coordinate of node i and node j respectively.

4.3 Routing Path Generation Procedure

The routing path algorithm greedily constructs a routing path $T = (V^T, E^T)$ by repeating the selection of one link that minimizes the cost function E when it is added into T, until every AP is included in the path. To evaluate the transmission delay in E accurately, a complete routing path is predicted by expanding the current partial path using the Dijkstra algorithm in terms of the link delay $(=1/s_k)$. Here, we note that the α-term in E is calculated only for the current path T with the selected link. In the procedure, the routing path $T = (V^T, E^T)$ is initialized with GW, and then, is sequentially constructed by selecting the best link minimizing the cost function of the predicted path one by one until every host is included in V^T.

1. Initialize the routing path T by $V^T = \{GW\}$ and $E^T = \phi$, and select any link whose speed is S_{route} or larger for use in the routing path.

2. Construct T by repeating the following two-step procedure until every host in V is included in T:

   (a) Select one unselected node that is adjacent to a node in the current path T in the following order:

   - AP,
   - constrained AP, which has only one route to GW,
   - isolated AP, which will be isolated otherwise due to the WDS clustering constraint, and
   - host.

   (b) Select one link that satisfies the following two conditions:

   - It connects the node in (a) and a node in T.

- When added to T, E with the complete path predicted in Section 4.4 is minimum.

4.4 Complete Routing Path Prediction

A complete routing path is predicted by expanding the current partial path T by selecting the links that connect the remaining hosts using the Dijkstra algorithm where the inverse of the link speed is used as the link weight.

1. Initialize the set of the unselected nodes, A, by $A = V$, and the decision variables for them, *weight labels* for propagation delays, and *route labels* for previous nodes in paths from GW, in the Dijkstra algorithm using the current partial path T as follows:

   (a) For weight labels:
      - set the obtained propagation delay for any node $\in T$, and
      - set ∞ for the remaining nodes.
   (b) For route labels:
      - set the previous node along the route from GW in T for any node in T, and
      - set ∞ for the remaining nodes.

2. Select one node (let node m) in A that has the smallest weight label.

3. Remove node m from A, and terminate the procedure if $A = \phi$.

4. Update the both labels of the nodes that are adjacent to node $m \in A \cap \notin V^T$.

Chapter 5

Extended Active AP Selection Algorithm

In this chapter, we present the active AP selection algorithm to consider the link speed change.

5.1   Problem Formulation

The extended active AP selection problem can be defined as follows:

1. Input

    – The same inputs as those for the routing path problem

2. Output

    – Set of active APs: V_{act}
    – Routing path: T

3. Constraints

    – Any host must be connected to the GW through active APs (host routing constraint).

4. Objective

    – The number of active APs should be minimized.
    – Holding the first objective, the same cost function E for the routing path should be minimized.

5.2   Active AP Selection Procedure

5.2.1   Sequential AP Deactivation

Starting from the initial state where every AP is selected as an active one, the active AP selection algorithm minimizes the number of active APs by sequentially deactivating one

active AP such that it does not only satisfy the constraints but also optimizes the selection index, until no more AP can be deactivated. In the following procedure, the *active AP* represents an AP that is activated in WIMNET, the *inactive AP* does an AP that is suspended, the *must-active AP* does an AP that cannot be suspended because of the constraints, and the *candidate AP* does an AP that can be a candidate as the next inactive AP among active APs.

1. Initialize the solution state by selecting all the APs for *active APs*, and the sets of *inactive APs* and *must-active APs* by null sets.

2. Apply the routing path algorithm in Section 4 for the *active APs* and the hosts to find the routing path. If a feasible routing path cannot be found here, terminate the procedure as an input error.

3. If every *active AP* becomes a *must-active AP*, output the current solution and terminate the procedure.

4. Select a *candidate AP* for the next deactivation from the *active APs*, such that:

   (a) it is not *must-active APs* and

   (b) it forwards packets from/to the least number of hosts in the routing path.

   This selection intends to select an AP whose deactivation causes the least influence to the routing path.

5. When the *candidate AP* is deactivated, check if any host on the downstream side of this AP in the routing path connected to the GW through other *active APs* or not. If this condition is not satisfied, mark it as *must-active AP*, and go to 3).

6. Apply the routing path algorithm for the *active APs* and the hosts. If a feasible routing path cannot be found, mark this *candidate AP* as a *must-active AP* and go to 3).

7. Deactivate the *candidate AP* and go to 3).

5.2.2 AP Reactivation for Active AP Minimization

After sequentially deactivating APs, our active AP selection algorithm further minimizes the number of active APs by repeating the reactivation of a deactivated AP such that two or more APs can be deactivated simultaneously after its reactivation.

1. Make a list of the deactivated APs by sorting them in the deactivated order by the procedure in Section 5.2.1 or by this AP reactivation procedure, and initialize the number of reactivated APs R_{AP} by 0.

2. Select the first AP in the list and reactivate it. Then, if two or more active APs can be deactivated simultaneously by satisfying the conditions, deactivate them and increment R_{AP} by 1. Otherwise, resume the previous state.

3. Remove the reactivated AP from the list. If the list is not empty, go to 2.

4. If $R_{AP} > 0$, go to 1. Otherwise, terminate the procedure.

5.2.3 Example

To illustrate the procedure in our algorithm, we consider the simple topology in Figure 5.1. In this topology, four APs are allocated at the corners of a $40m \times 40m$ square where one AP is the GW, and two hosts are allocated at the $40m$ distance from the non-GW APs in the opposite directions from the GW. $S_{route} = 40Mbps$ is used. Thus, the GW can connect with any AP and cannot directly connect with any host.
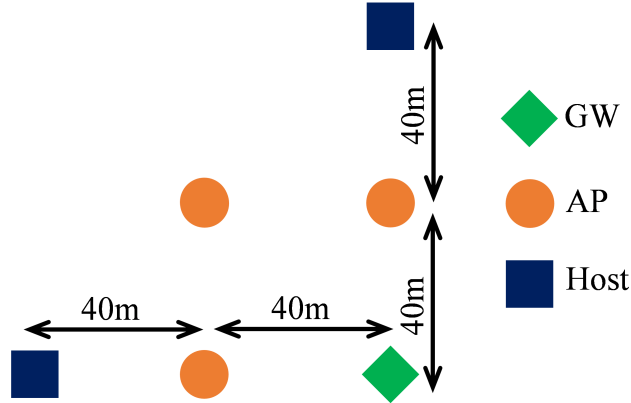
Figure 5.1: Simple topology for algorithm illustration.

For this topology, the sequential deactivation procedure in the algorithm first deactivates the farthest AP from the GW as shown in Figure 5.2, because it does not forward any host in the routing path that is composed of the shortest path between each host and the GW. Then, it cannot deactivate any other AP, because each host cannot connect with any other active AP in this state. After that, in the deactivation/reactivation procedure, when this deactivated AP is reactivated, the two hosts connect with this AP and the other two APs are deactivated simultaneously. Thus, the number of active APs is minimized to two as shown in Figure 5.3.
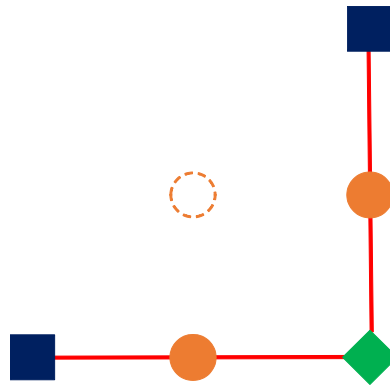
Figure 5.2: Solution after sequential AP deactivation.

5.3 Extensions for Multiple Gateways

In this section, we present the extensions of the active AP selection algorithm to consider multiple GWs, the limited number of hops, and the minimum host throughput. For our
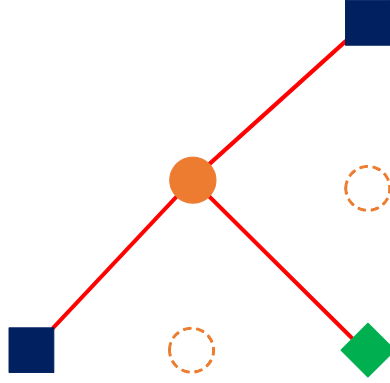
Figure 5.3: Solution after AP reactivation/deactivation.

extensions, we modify the input and the output of the algorithm. Besides, we present the plural AP deactivation procedure to deactivate plural APs simultaneously, to reduce the algorithm execution time.

In the algorithm input, one or more nodes can be GWs. Besides, the link speed estimation equation and the interference threshold are added.

- IEEE802.11ac link speed estimation equation

- 11ac link speed threshold for interferences between links

In the algorithm output, each GW should compose a routing tree connecting hosts, such that the root is a GW, the leaves are hosts, and every host is included in one routing tree. Thus, the output should be a *routing forest*.

- A set of routing trees or a *routing forest*

5.4   Plural AP Deactivation for Preprocessing

To reduce the running time of the algorithm, plural APs are deactivated simultaneously as the preprocessing in the extended algorithm. Because at most one AP exists between a GW and a host in the previous extension, an AP located around the middle between a GW and a host is effective as a relay AP to boost the link speed. Thus, APs near GWs or hosts are deactivated in this procedure.

1. Calculate the distance between any pair of a GW and a host.

2. Select the largest one in 1). Let this distance be L.

3. Select an AP whose distances from the half of the GWs are smaller than $1/3L$ or larger than $2/3L$.

4. Deactivate each AP selected in 3) in descending order of the shortest distance from a GW. If the deactivation of an AP does not cover the host covering constraint, stop this deactivation.

5.5 Modification of Adopted Routing Algorithm

To consider multiple GWs and the limited number of hops, we adopt our new routing algorithm for WIMNET that considers both conditions in [5]. Specifically, we replace the routing algorithm from Section 5.2.1 in the following steps:

2) Apply the *routing algorithm* in [5] for the *active APs* and the hosts to find the routing tree. If a feasible routing forest cannot be found here, terminate the procedure as an input error.

6) Apply the *routing algorithm* for the *active APs* and the hosts. If a feasible routing forest cannot be found, mark this *candidate AP* as a *must-active AP* and go to 3).

5.6 Minimum Host Throughput

After applying the routing algorithm, we calculate the estimated throughput for every host by Eq. (5.1) if a feasible routing forest is obtained:

$$et_i = \frac{1}{\sum\limits_{k \in P_i} \frac{1}{s_k}} \tag{5.1}$$

where s_k represents the speed for link k and P_i does the set of links in the routing path between the GW and host i. $\frac{1}{s_k}$ represents the estimated delay to send 1 bit through link k. Thus, $\sum\limits_{k \in P_i} \frac{1}{s_k}$ represents the estimated total delay to send 1 bit through the links connecting the GW and host i in the routing path. The inverse becomes the estimated throughput between the GW and host i. Then, if this estimated throughput for any host is smaller than the given minimum host throughput, the obtained routing forest is regarded as infeasible.

5.7 Related Works

Within our survey, we cannot find a paper dealing with the same active AP selection problem for WMNs. In [67], Avakul et al. discussed the multiple-tiers WMN project for disaster recovery process, and illustrated merits in optimizing the number of mesh routers to achieve the optimum performance. In [68], Hu presented a GW selection problem in a WMN to select a minimal number of non-GW nodes and upgrade them to GWs to improve the delivery ratio of the network to a given threshold, where the number of active APs is not reduced.

In [69], Mamechaoui et al. surveyed existing approaches dedicated to energy conservations for WMNs including the switching scheme that aims to powering on the minimum number of devices [70]. In [71], Pathak et al. surveyed fundamental design problems of interference modeling, power control, topology control, link scheduling, and routing with special stress on joint design methods for WMNs. In [72], Benyamina et al. also surveyed design aspects and examined methods that have been proposed to improve the performance of already deployed ones or by careful planning of deployments for WMN.

Chapter 6

WIMNET Simulator for Throughput Changes

In this chapter, we present an extension of the WIMNET simulator [3] to simulate the various link speed including the AP-host link. The WIMNET simulator has been developed in our group to evaluate the performance of WMN and multiple WLANs in conventional PCs. In this simple network simulator, every link activation is synchronously controlled by a single clock called a *time slot* and the sequence of one link activation including the random back-off, the data frame transmission, and the acknowledgement reception is completed within the duration time of a single or multiple time slots.

6.1 Maximum Link Speed and Time Slot Interval

From throughput measurement results in Section 4.2, we select $120Mbps$ for the maximum link speed in the extended WIMNET simulator. We assume that each frame transmits $1,500Bytes (= 12Kbits)$ data considering the Ethernet MTU size. Then, we set 0.1 msec for one time slot duration time, which realizes $120Mbps (= 12Kbits/0.1msec)$.

6.2 Realization of Arbitrary Link Speed

As discussed before, an integer number of time slots can be used to simulate one link activation, which allows only discrete link speeds in the WIMNET simulator. In our extension, we calculate the two integer numbers of time slots that are closest to the real number of time slots representing the *target link speed*, and realize this link speed by using alternatively either integer number of time slots such that the *average link speed* is equal to the target one. The following procedure describes the steps in our proposal.

1. Initialization
   Before starting communications, the following procedure is executed:

   (a) Calculate the target real number of time slots TN_k to realize the given target link speed for link k:
   $$TN_k = \frac{120}{s_k} \tag{6.1}$$

(b) Calculate the two integer numbers of time slots TU_k and TL_k that are closest to TN_k for link k:

$$TU_k = \lceil TN_k \rceil, \quad TL_k = \lfloor TN_k \rfloor \tag{6.2}$$

where the function $\lceil x \rceil$ returns the smallest integer that is not smaller than x, and the function $\lfloor x \rfloor$ returns the largest integer that is not larger than x.

(c) Randomly select either of TU_k or TL_k for the initial number of time slots, set it for the initial value of the accumulated number of activated time slots AN_k, and initialize the accumulated number of link activations AL_k for link k by 1.

2. Time slot control during communications
   Each time link k is activated, the following procedure is executed:

(a) Calculate the average number of activated time slots AV_k:

$$AV_k = \frac{AN_k}{AL_k}. \tag{6.3}$$

(b) Select the number of time slots for the link activation:
   if $AV_k < TN_k$, then select TU_k, else select TL_k.

(c) Update AN_k and AL_k.

6.3 AP-Host Link Consideration

Previously, no host explicitly appears in the WIMNET simulator. Instead, as inputs to the simulator, each AP is associated with a given number of hosts. We extend the WIMNET simulator to use the AP-host links selected by the extended routing path algorithm.

Chapter 7

Evaluation by Simulations

In this chapter, we evaluate the extended active AP selection algorithm and multiple GWs through extensive simulations in multiple instances using the extended WIMNET simulator.

7.1 Simulation Instances

7.1.1 Active AP Selection

For active AP selection's simulated instances, we adopt a grid topology where 3×5 ($N = 15$) APs are allocated with the same interval on a rectangular field. This *AP interval* is fixed to $30m$. The center AP is selected as the GW to the Internet. Any link can be interfered with other links within $110m$ distance in an open space. We give the position of every AP and host, and estimate the link speed between two nodes by using the Eq. (4.2). 100 hosts are randomly allocated on the field, uniformly for *instance 1*, with the higher density on the field middle for *instance 2*, and with the higher density on the field edge for *instance 3*. The fraction of the host density is 1 : 3.

7.1.2 Multiple Gateway

Figures 7.1-7.3 show three simulated topologies in our multiple GWs simulations with the $150m \times 150m$ square field, where a square represents an host, a circle does an AP, and a rhombus does a GW (AP). 4×4 APs are allocated regularly with the $30m$ interval, and 50 hosts are randomly allocated on the entire field uniformly in *Topology 1*, intensively on the upper field in *Topology 2*, and intensively on the lower field in *Topology 3*. The number of GWs is changed from 1 to 3. Specifically, the AP at the left-bottom corner is selected for the first GW. Then, its right AP is additionally selected for the second GW, and its upper AP is selected for the third GW. We note that we use the same topology for APs in these instances, although the four APs in the first row may not be necessary in *Topology 3*.

7.2 Simulation Results

Tables 7.1 to 7.3 show the number of active APs and the overall throughput before and after applying the AP reactivation in the extended active AP selection algorithm to evaluate its effectiveness when the minimum link speed for the routing path S_{route} is changed from
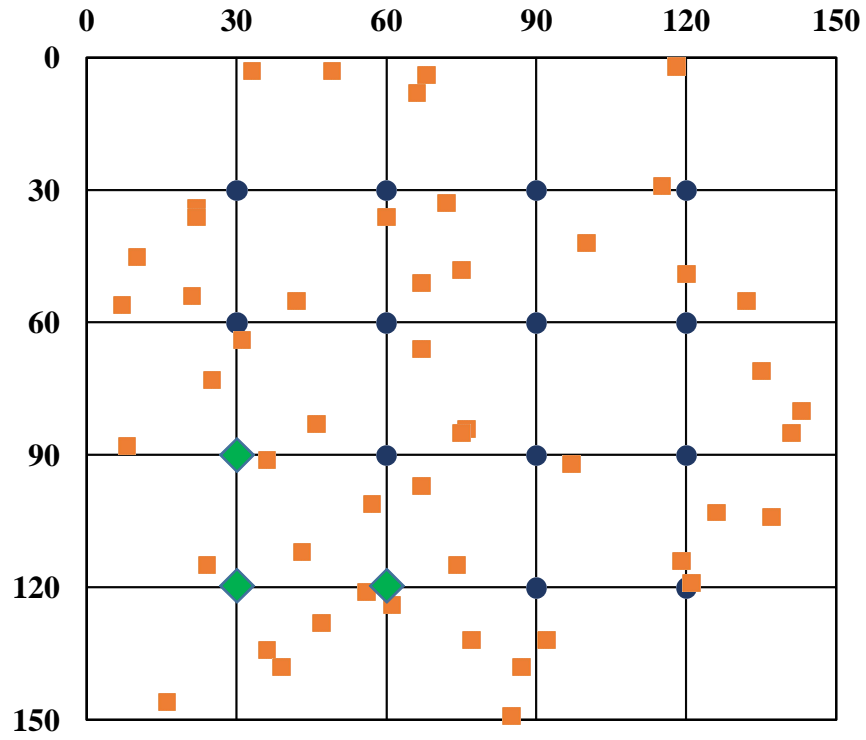
Figure 7.1: Multiple gateway *Topology 1*.
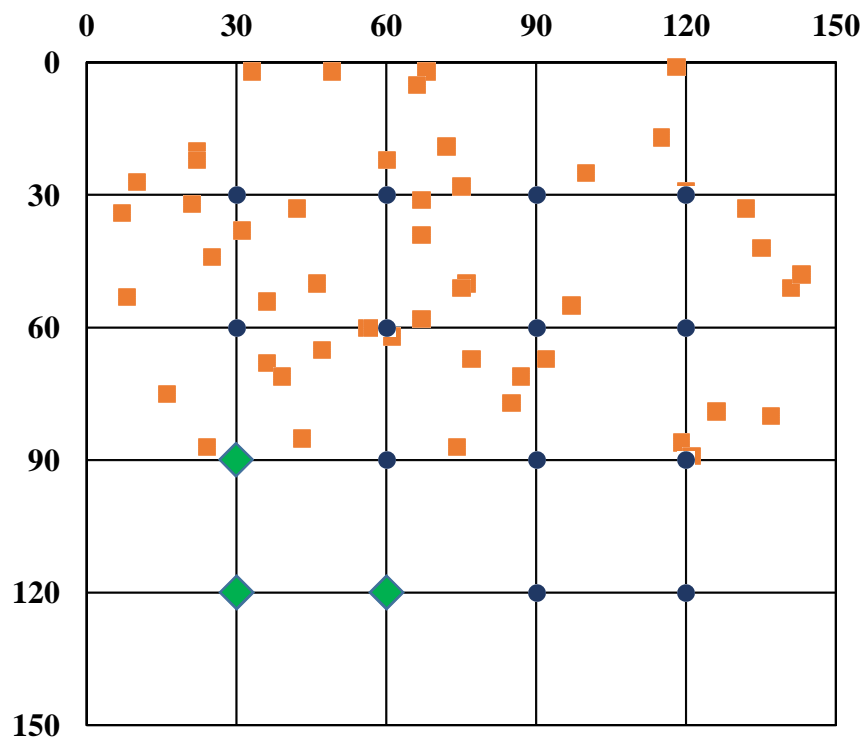
Figure 7.2: Multiple gateway *Topology 2*.
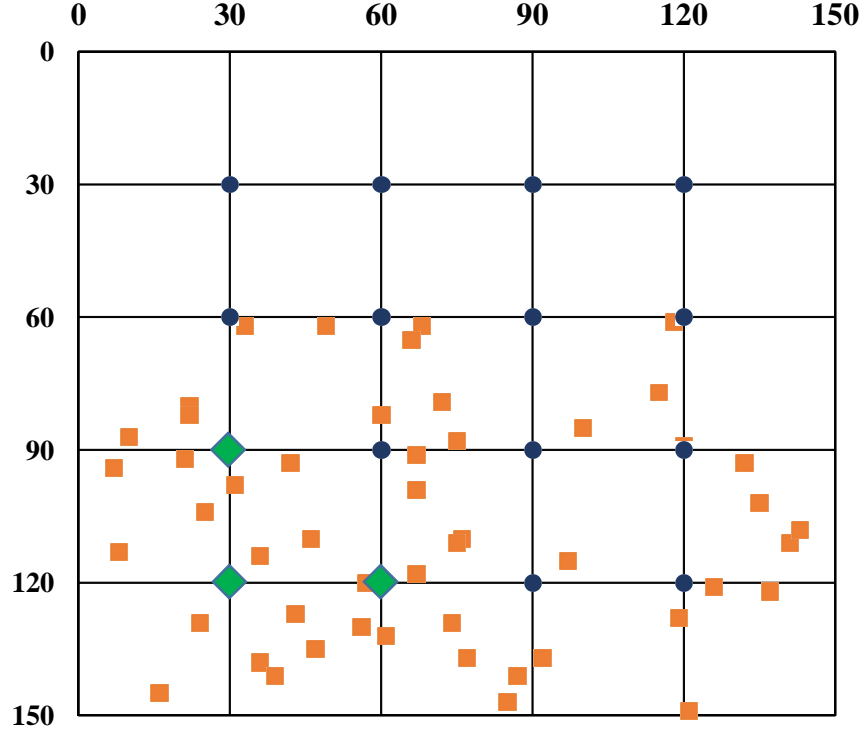
Figure 7.3: Multiple gateway *Topology 3*.

$10Mbps$ to $50Mbps$. At $S_{route} = 10Mbps$, the link distance is about $85m$ from Figure 4.1. This means that at least three active APs including the fixed GW are necessary to cover all the hosts in any instance, because the GW cannot cover the hosts at both sides of the field.

Table 7.1: Simulation results for *instance 1*.

S_{route} ($Mbps$)	Before Reactivation		After Reactivation	
	# of Active APs	Throughput ($Mbps$)	# of Active APs	Throughput ($Mbps$)
5	4	31.3	3	29.3
10	4	31.3	3	29.3
20	5	32.2	3	29.4
30	6	32.0	6	32.0
40	8	31.4	7	30.0
50	8	26.9	8	26.9

From the results in these tables, we found the following facts:

1. The AP reactivation in the algorithm can further reduce the number of active APs with the similar overall throughput.

2. The algorithm can minimize the number of active APs if a sufficiently small value is adopted for the S_{route}.

3. The overall throughput is slightly changed even for the same number of active APs depending on S_{route}.

Table 7.2: Simulation results for *instance 2*.

S_{route} (*Mbps*)	Before Reactivation		After Reactivation	
	# of Active APs	Throughput (*Mbps*)	# of Active APs	Throughput (*Mbps*)
5	4	31.4	3	30.2
10	4	31.4	3	30.7
20	5	32.8	3	30.8
30	5	31.7	6	30.6
40	7	30.8	7	30.8
50	9	30.0	9	30.0

Table 7.3: Simulation results for *instance 3*.

S_{route} (*Mbps*)	Before Reactivation		After Reactivation	
	# of Active APs	Throughput (*Mbps*)	# of Active APs	Throughput (*Mbps*)
5	4	31.4	3	24.5
10	4	31.4	3	29.7
20	5	32.4	3	29.6
30	5	32.3	3	29.1
40	7	30.0	7	30.0
50	8	27.0	8	27.0

If different values can properly be assigned to S_{route} of different links, the overall throughput may be improved with the same number of active APs, because the traffic of a link between APs is usually much higher than that of a link between an AP and a host. This assignment of S_{route} for the further active AP minimization and the overall throughput maximization will be in our future works.

Figures 7.4 to 7.6 illustrate the input network topology and the best solution found by the algorithm in terms of the number of active APs and the overall throughput for each instance respectively. To show the connections between hosts and active APs, we used different symbols to represent hosts connecting different APs, where a *crisscross* represents a host connecting with the left AP, an *x-mark* does a host with the center AP, and a *triangle* does a host with the right AP. Because the center AP or GW does not need communications with other APs, the largest number of hosts are associated with it.

7.2.1 Results for Different Gateways

To further reduce the number of active APs, we investigate simulation results when the GW is moved from the center AP to its neighbors. Tables 7.4 to 7.6 show the number of active APs and the overall throughput after applying the AP reactivation when the GW is moved to the immediate left AP or the left lower AP of the original one. In any instance, when the immediate left AP is selected as the GW, the number of active APs can be reduced to the minimum of two, if S_{route} is properly assigned.
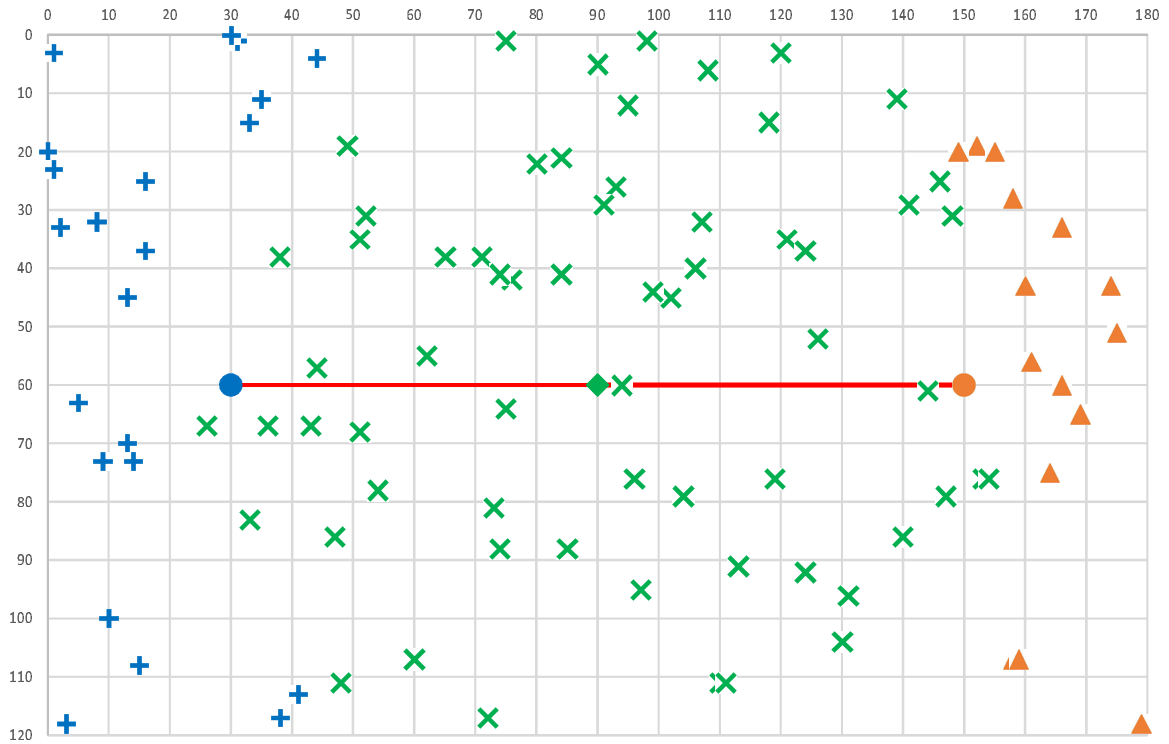
Figure 7.4: Input topology and best solution for *instance 1*.
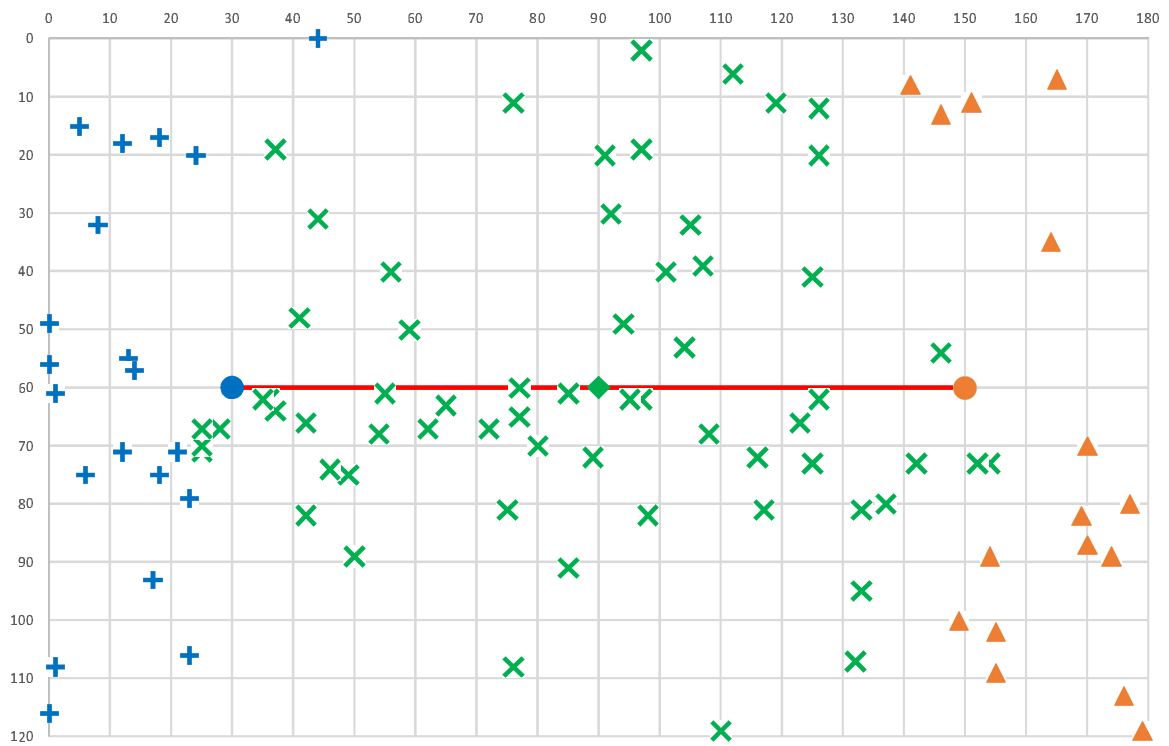
Figure 7.5: Input topology and best solution for *instance 2*.
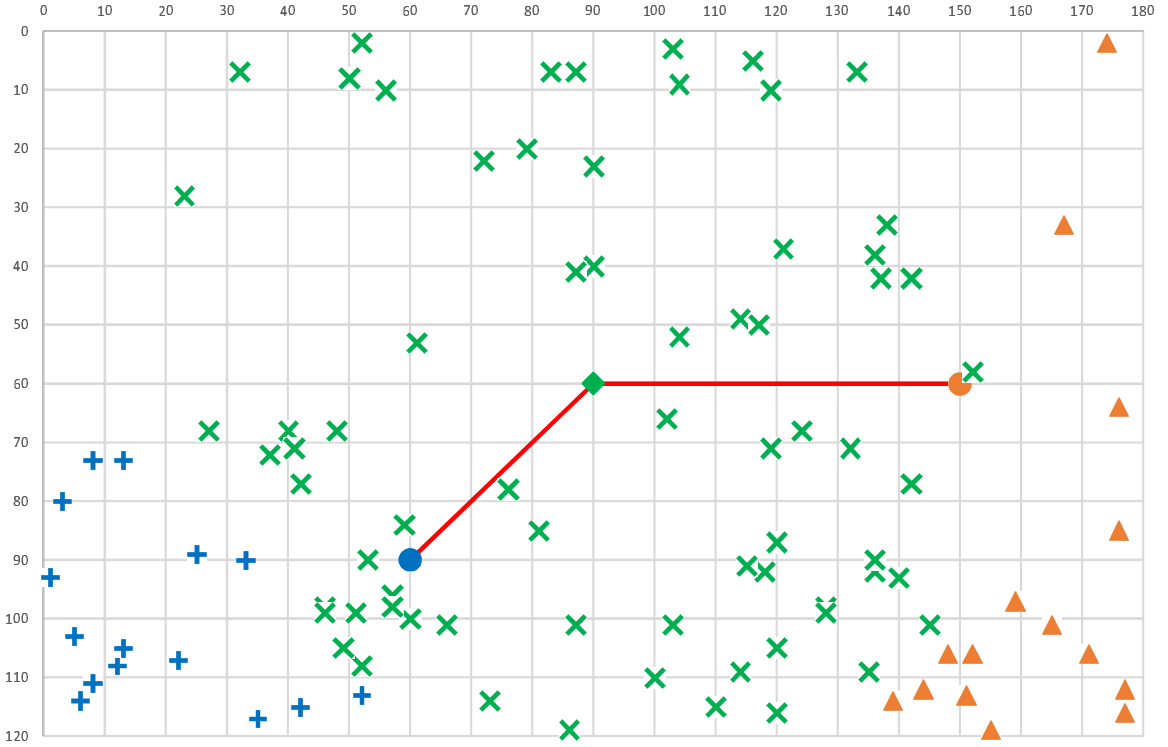
Figure 7.6: Input topology and best solution for *instance 3*.

Table 7.4: Simulation results for *instance 1*.

S_{route} (*Mbps*)	Immediate Left AP		Left Lower AP	
	# of Active APs	Throughput (*Mbps*)	# of Active APs	Throughput (*Mbps*)
5	2	27.2	3	20.3
10	2	27.2	3	22.6
20	5	29.1	5	25.6
30	5	28.9	6	23.3

Table 7.5: Simulation results for *instance 2*.

S_{route} (*Mbps*)	Immediate Left AP		Left Lower AP	
	# of Active APs	Throughput (*Mbps*)	# of Active APs	Throughput (*Mbps*)
5	2	28.8	3	26.1
10	3	29.5	4	27.1
20	4	30.5	4	27.0
30	5	30.2	5	25.4

7.2.2 Comparison with All Active AP Case

To evaluate the throughput performance of a solution by the algorithm, we examine the throughput when all of the 15 APs are activated for each of the three GW positions in the

Table 7.6: Simulation results for *instance 3*.

S_{route} (*Mbps*)	Immediate Left AP		Left Lower AP	
	# of Active APs	Throughput (*Mbps*)	# of Active APs	Throughput (*Mbps*)
5	3	25.4	3	24.2
10	2	25.3	3	25.6
20	4	26.0	4	27.2
30	5	22.7	4	27.0

three instances. Table 7.7 summarizes the overall throughput for each case. The comparison with the previous results show that our algorithm can reduce the number of active APs drastically from 15 to 2 or 3 while maintaining the similar throughput. This fact confirms the effectiveness of the proposed algorithm.

Table 7.7: Throughputs for all active APs.

Gateway Position	Center (*Mbps*)	Immediate Left (*Mbps*)	Left Lower (*Mbps*)
instance 1	32.9	30.9	27.2
instance 2	33.8	32.8	29.8
instance 3	32.7	29.7	29.8

7.2.3 Results for Host Mobility

To show the effectiveness of the active AP selection algorithm under host mobility, we investigate simulation results for *instance 1* when the host locations and the host densities are slightly different from the given topology. In these simulations, the network configuration of the active APs and the routing path is first found by applying the algorithm to the given topology and is fixed. Then, each host location is randomly shifted within a fixed distance ($1m$-$10m$) from the original location, or the number of hosts is reduced by a fixed rate (10%-50%) by randomly selecting removed hosts.

Tables 7.8 and 7.9 show the throughput results for shifted host locations and reduced host densities respectively. In any case, the overall throughput is not degraded from the original case ($29.3Mbps$) in Table 7.1, although the network configuration is fixed while the host locations/densities are changed. This indicates that the network configuration found by the algorithm for full possible host locations is effective for WIMNET. The active AP selection algorithm should be performed when the topology of GW/AP locations and possible host locations is changed.

7.2.4 Results for Different AP Intervals

To examine the performance of the algorithm for different AP intervals in the field, we additionally simulated *instance 1* with three AP intervals at $10m$, $20m$, and $40m$. In any interval, the GW is assigned at the center and the AP locations become symmetric in the network field, where we use the same host locations and $S_{route} = 20Mbps$. Table 7.10

Table 7.8: Throughputs for *instance 1* with shifted host locations.

Shift (m)	Throughput ($Mbps$)
1	29.2
2	29.5
3	29.6
5	29.4
10	27.0

Table 7.9: Throughputs for *instance 1* with reduced host densities.

Reduce (%)	Throughput ($Mbps$)
10	29.1
20	29.7
30	29.6
40	28.7
50	29.4

compares the number of active APs and the throughput between the algorithm case and the all active AP case. This table indicates that the throughput difference is small even if the AP interval is changed. This reason can come from the fact that the GW becomes the bottleneck of whole communications where the total capacity of the wireless links is limited.

Table 7.10: Throughputs for *instance 1* with different AP intervals.

| AP Interval (m) | Algorithm | | All Active APs | |
	# of APs	Throughput ($Mbps$)	# of APs	Throughput ($Mbps$)
15	3	29.4	77	33.1
20	3	29.3	45	33.1
30	3	29.4	15	32.9
40	5	31.5	15	32.5

7.2.5 Results for Multiple Gateways

Tables 7.11-7.13 show simulation results for them with/without considering the minimum host throughput with the $30Mbps$ threshold respectively. The number of active APs by the algorithm and the corresponding total throughput by the WIMNET simulator are summarized. In each table, " - " indicates no result obtained by the algorithm due to constraints. From these results, we obtain the following observations:

- The total throughput is nearly proportional to the number of GWs.

- The minimum host throughput consideration can disturb the minimization of active APs.

- The smaller number of active APs can improve the throughput in general.

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- The smaller number of GWs can reduce the number of active APs if the minimum host throughput is not considered, because a GW cannot be deactivated.

- The throughput for *Topology 3* is best because the average distance between a GW and a host is the smallest.

Table 7.11: Simulation results for *Topology 1*.

Minimum Host Throughput	3GWs		2GWs		1GW	
	APs	Mbps	APs	Mbps	APs	Mbps
Yes	16	168.1	16	122.4	16	64.8
	10	168.7	8	133.9	11	68.3
	9	161.4	7	133.7	-	-
	8	179.4	6	135.1	-	-
No	16	168.1	16	122.4	16	64.8
	10	168.7	8	133.9	11	68.3
	9	161.3	7	133.7	10	68.1
	8	180.9	6	135.1	9	68.5
	7	194.4	-	-	8	68.5
	6	179.6	-	-	7	68.4
	-	-	-	-	6	67.9
	-	-	-	-	5	68.1

Table 7.12: Simulation results for *Topology 2*.

Minimum Host Throughput	3GWs		2GWs		1GW	
	APs	Mbps	APs	Mbps	APs	Mbps
Yes	16	144.8	16	105.5	16	58.4
	10	122.0	7	109.3	11	62.1
	-	-	6	111.3	-	-
No	16	144.8	16	105.5	16	58.4
	10	122.0	7	109.3	11	62.1
	9	122.0	6	111.3	10	62.1
	8	121.0	-	-	9	62.1
	7	128.7	-	-	8	62.9
	6	142.9	-	-	7	62.8
	-	-	-	-	6	64.2
	-	-	-	-	5	63.1
	-	-	-	-	4	63.1

7.2.6   CPU Time Results

Table 7.14 compares the CPU time of the algorithm on Intel (R) Core i7-3770 (3.40 Ghz) with Ubuntu12.04 Linux2.6.32 as virtual OS, when the plural AP deactivation is adopted (= yes) and is not (= no). This table indicates that this preprocessing can drastically reduce the CPU time.

Table 7.13: Simulation results for *Topology 3*.

Minimum Host Throughput	3GWs		2GWs		1GW	
	APs	Mbps	APs	Mbps	APs	Mbps
Yes	16	197.1	16	136.4	16	66.3
	6	203.5	6	137.8	6	68.8
	5	193.9	5	139.4	5	68.9
	-	-	-	-	4	69.2
No	16	197.1	16	136.4	16	66.3
	6	203.5	6	137.8	6	68.8
	5	193.9	5	139.4	5	68.9
	-	-	-	-	4	69.2

Table 7.14: Algorithm CPU time.

Topology	Minimum Host Throughput	3GWs (sec)		2GWs (sec)		1GW (sec)	
		Yes	No	Yes	No	Yes	No
1	Yes	62.0	76.3	12.2	47.8	56.4	93.7
	No	24.4	43.4	11.9	48.5	21.6	35.4
2	Yes	42.9	147.7	8.6	42.5	48.8	75.8
	No	24.1	51.6	8.8	42.9	21.5	33.0
3	Yes	10.9	46.1	11.6	54.4	10.7	39.6
	No	10.8	46.1	11.6	53.5	10.6	39.3

7.3 Summary of Evaluations

To efficiently adopt the high-speed IEEE802.11n protocol by considering link speed changes to the WIMNET, we had presented the extended active AP selection algorithm with extensions of the routing path algorithm and the WIMNET simulator. Besides, we consider the multiple GWs, hop limitation multiple GWs, and the minimum host throughput for the IEEE802.11ac protocol. To reduce the computation time, we also introduced the plural AP deactivation procedure using the feature of this two-hop WIMNET. We verify the effectiveness of our proposal through simulations in multiple topologies.

Chapter 8

Conclusion

In this dissertation, we studied the extensions of the active AP selection algorithm for wireless mesh networks under practical conditions.

Firstly, we introduced related wireless network technologies including the IEEE 802.11n protocol, the IEEE 802.11ac protocol, and the wireless mesh networking technology.

Secondly, we presented throughput measurements of the IEEE 802.11ac and IEEE 802.11n protocols in various conditions using devices in three vendors. From our measurement results, we generated an equation for the link speed estimation from the link distance, which is used in the active AP selection algorithm and the WIMNET simulator.

Thirdly, we presented the extended active AP selection algorithm to consider practical conditions for real WIMNET. To reduce the computation time, we also introduced the plural AP deactivation procedure using the feature of this two-hop WIMNET. Besides, we extended the WIMNET simulator.

Finally, we verified the effectiveness of our proposal through extensive simulations using the WIMNET simulator.

In future studies, we will study the proper assignment of the minimum link speed parameter that is critical for the active AP minimization and the overall throughput maximization, the proper handling of dynamic traffic changes, the further algorithm extension to different hop limitations, and the system implementation for real networks.

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