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 IEEE 802.11n 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.
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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
not necessary in conventional situations where all the APs are functioning properly. Redundant APs are activated, the operation costs of WIMNET can increase, including power consumption and the device maintenance [11]. Besides, interferences among APs 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 selection of active APs. Therefore, in [8], we defined the active AP selection problem as a combinatorial optimization problem, and proposed a heuristic algorithm to select a set of active APs so 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]/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 by adopting the multiple-input-multiple-output (MIMO) channel, the frame aggregation channel bonding and other technologies [12].

Inexpensive commercial products implementing these protocols have become available. They include 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], the 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
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 under variable condition.

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

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

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

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

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.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>Wireless network bearer operating in the 5 GHz ISM band, data rate up to 54Mbps</td>
</tr>
<tr>
<td>802.11b</td>
<td>Operate in the 2.4 GHz ISM band, data rates up to 11Mbps</td>
</tr>
<tr>
<td>802.11c</td>
<td>Covers bridge operation that links to LANs with a similar or identical MAC protocol</td>
</tr>
<tr>
<td>802.11d</td>
<td>Support for additional regulatory differences in various countries</td>
</tr>
<tr>
<td>802.11e</td>
<td>QoS and prioritization, an enhancement to the 802.11a and 802.11b WLAN specifications</td>
</tr>
<tr>
<td>802.11f</td>
<td>Inter-Access Point Protocol for handover, this standard was withdrawn</td>
</tr>
<tr>
<td>802.11g</td>
<td>Operate in 2.4 GHz ISM band, data rates up to 54Mbps</td>
</tr>
<tr>
<td>802.11h</td>
<td>Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC)</td>
</tr>
<tr>
<td>802.11i</td>
<td>Authentication and encryption</td>
</tr>
<tr>
<td>802.11j</td>
<td>Standard of WLAN operation in the 4.9 to 5 GHz band to conform to the Japan’s rules</td>
</tr>
<tr>
<td>802.11k</td>
<td>Measurement reporting and management of the air interface between several APs</td>
</tr>
<tr>
<td>802.11l</td>
<td>Reserved standard, to avoid confusion</td>
</tr>
<tr>
<td>802.11m</td>
<td>Provides a unified view of the 802.11 base standard through continuous monitoring, management and maintenance</td>
</tr>
<tr>
<td>802.11n</td>
<td>Operate in the 2.4 and 5 GHz ISM bands, data rates up to 600Mbps</td>
</tr>
<tr>
<td>802.11o</td>
<td>Reserved standard, to avoid confusion</td>
</tr>
<tr>
<td>802.11p</td>
<td>To provide for wireless access in vehicular environments (WAVE)</td>
</tr>
<tr>
<td>802.11r</td>
<td>Fast BSS Transition, supports VoWiFi handoff between access points to enable VoIP roaming on a WiFi network with 802.1X authentication</td>
</tr>
<tr>
<td>802.11s</td>
<td>Wireless mesh networking</td>
</tr>
</tbody>
</table>
Table 2.1: IEEE 802.11 Standards.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11t</td>
<td>Wireless Performance Prediction (WPP), this standard was cancelled</td>
</tr>
<tr>
<td>802.11u</td>
<td>Improvements related to &quot;hotspots&quot; and 3rd party authorization of clients</td>
</tr>
<tr>
<td>802.11v</td>
<td>To enable configuring clients while they are connected to the network</td>
</tr>
<tr>
<td>802.11w</td>
<td>Protected Management Frames</td>
</tr>
<tr>
<td>802.11x</td>
<td>Reserved standard, to avoid confusion</td>
</tr>
<tr>
<td>802.11y</td>
<td>Introduction of the new frequency band, 3.65-3.7GHz in US besides 2.4 and 5 GHz</td>
</tr>
<tr>
<td>802.11z</td>
<td>Extensions for Direct Link Setup (DLS)</td>
</tr>
<tr>
<td>802.11aa</td>
<td>Specifies enhancements to the IEEE 802.11 MAC for robust audio video (AV) streaming</td>
</tr>
<tr>
<td>802.11ac</td>
<td>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</td>
</tr>
<tr>
<td>802.11ad</td>
<td>Wireless Gigabit Alliance (WiGig), providing very high throughput at frequencies up to 60GHz</td>
</tr>
<tr>
<td>802.11ae</td>
<td>Prioritization of management frames</td>
</tr>
<tr>
<td>802.11af</td>
<td>WiFi in TV spectrum white spaces (often called White-Fi)</td>
</tr>
<tr>
<td>802.11ah</td>
<td>WiFi uses unlicensed spectrum below 1GHz, smart metering</td>
</tr>
<tr>
<td>802.11ai</td>
<td>Fast initial link setup (FIIS)</td>
</tr>
<tr>
<td>802.11aj</td>
<td>Operation in the Chinese Milli-Meter Wave (CMMW) frequency bands</td>
</tr>
<tr>
<td>802.11ak</td>
<td>General links</td>
</tr>
<tr>
<td>802.11aq</td>
<td>Pre-association discovery</td>
</tr>
<tr>
<td>802.11ax</td>
<td>High efficiency WLAN, providing 4x the throughput of 802 11ac</td>
</tr>
<tr>
<td>802.11ay</td>
<td>Enhancements for Ultra High Throughput in and around the 60GHz Band</td>
</tr>
<tr>
<td>802.11az</td>
<td>Next generation positioning</td>
</tr>
<tr>
<td>802.11mc</td>
<td>Maintenance of the IEEE 802.11m standard</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Max Data Rate (Mbps)</th>
<th>Frequency Band (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Modulation Scheme</th>
<th>Spatial Strea</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>54</td>
<td>5</td>
<td>20</td>
<td>OFDM</td>
<td>1</td>
</tr>
<tr>
<td>802.11b</td>
<td>11</td>
<td>2.4</td>
<td>20</td>
<td>DSSS</td>
<td>1</td>
</tr>
<tr>
<td>802.11g</td>
<td>54</td>
<td>2.4</td>
<td>20</td>
<td>OFDM/DSSS</td>
<td>1</td>
</tr>
<tr>
<td>802.11n</td>
<td>600</td>
<td>2.4/5</td>
<td>20/40</td>
<td>OFDM</td>
<td>4</td>
</tr>
<tr>
<td>802.11ac</td>
<td>1300</td>
<td>5</td>
<td>20/40/80/160</td>
<td>OFDM</td>
<td>8</td>
</tr>
</tbody>
</table>

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 40 MHz bandwidth channels, MIMO, frame aggregation, and security improvements to 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.

<table>
<thead>
<tr>
<th>Specification</th>
<th>IEEE 802.11n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Simultaneous Uninterrupted Channel</td>
<td>2 ch</td>
</tr>
<tr>
<td>Available Channel</td>
<td>13 ch</td>
</tr>
<tr>
<td>Max Speed</td>
<td>600 Mbps</td>
</tr>
<tr>
<td>Max Bandwidth</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Max Spatial Streams</td>
<td>4</td>
</tr>
<tr>
<td>Subcarrier Modulation Scheme</td>
<td>64 QAM</td>
</tr>
<tr>
<td>Release Date</td>
<td>Sept 2009</td>
</tr>
</tbody>
</table>

We can use the IEEE 802.11n in either the 2.4 GHz or 5 GHz band. Nowadays, the 5 GHz band 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 V with adjacent channel overlapping will suffer from interference between each other and 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.

![WiFi channels in 2.4 GHz band](image)

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.

![WiFi channels in 5 GHz band](image)

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 802.11n’s throughput.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 MHz</td>
</tr>
<tr>
<td>1 Stream</td>
<td>72.2Mbps</td>
</tr>
<tr>
<td>2 Streams</td>
<td>144.4Mbps</td>
</tr>
<tr>
<td>3 Streams</td>
<td>216.7Mbps</td>
</tr>
<tr>
<td>4 Streams</td>
<td>288.9Mbps</td>
</tr>
</tbody>
</table>

Division Multiplexing (SDM), within one spectral channel of bandwidth. Figure 2.5 the comparison between the previous technologies, Single Input Single Output (SISO) mission and MIMO transmission. SISO uses one transmit antenna and one receive an whereby 802.11n uses up to four transmit and receive antennas between devices. SIS0 system allowed only one antenna, active during data transmissions, while all antennas 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 improve through frame aggregation in the MAC layer. Frame aggregation can transmit mu frames by one big frame with a single pre-amble and header information to reduce overhead by them.

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

While in the physical layer, 802.11n use the 64 Quadrature Amplitude Modulation (C scheme under the Modulation and Coding Scheme (MCS). QAM is a form of modul technique used for modulating digital information signals. QAM exists in both analogue digital formats. For 802.11n, the digital QAM format is used and named as Quantized C In QAM, digital information is encoded in bit sequences represented by discrete ampl levels of an analog carrier. Two carriers are shifted in phase of 90° with output vai both amplitude and phase. For 64 QAM, six bits of input alters the phase and amplitu 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>
<thead>
<tr>
<th>Specification</th>
<th>IEEE 802.11ac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Simultaneous Uninterrupted Channel</td>
<td>9 ch</td>
</tr>
<tr>
<td>Available Channel</td>
<td>19 ch</td>
</tr>
<tr>
<td>Max Speed</td>
<td>6.93 Gbps</td>
</tr>
<tr>
<td>Max Bandwidth</td>
<td>160 MHz</td>
</tr>
<tr>
<td>Max Spatial Streams</td>
<td>8</td>
</tr>
<tr>
<td>Subcarrier Modulation Scheme</td>
<td>256 QAM</td>
</tr>
<tr>
<td>Release Date</td>
<td>Dec 2012</td>
</tr>
</tbody>
</table>

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 802.11ac's throughput.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>20 MHz</th>
<th>40 MHz</th>
<th>80 MHz</th>
<th>160 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Stream</td>
<td>86.7 Mbps</td>
<td>200 Mbps</td>
<td>433.3 Mbps</td>
<td>866.7 Mbps</td>
</tr>
<tr>
<td>2 Streams</td>
<td>173.3 Mbps</td>
<td>400 Mbps</td>
<td>866.7 Mbps</td>
<td>1733 Mbps</td>
</tr>
<tr>
<td>3 Streams</td>
<td>288.9 Mbps</td>
<td>600 Mbps</td>
<td>1300 Mbps</td>
<td>2340 Mbps</td>
</tr>
<tr>
<td>4 Streams</td>
<td>346.7 Mbps</td>
<td>800 Mbps</td>
<td>1733 Mbps</td>
<td>3466 Mbps</td>
</tr>
<tr>
<td>8 Streams</td>
<td>693.4 Mbps</td>
<td>1600 Mbps</td>
<td>3466 Mbps</td>
<td>6933 Mbps</td>
</tr>
</tbody>
</table>

beamforming technology that generates directional radio signals. This is far faster than 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 technique. In beamforming, a sender detects where the receiver are and transmits data through amplifying the signal in their direction(s). The focus of radio frequency energy toward 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.](image)

The 802.11ac also inherits the A-MSDU and A-MPDU from 802.11n, and allows 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 packet arrives at the destination node. 802.11ac adopts 400 ns as the guard interval 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 802.11) and the 256 QAM constellation.
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.
- **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 connections between home.

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

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

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

- **Transportation systems**: To provide transportation support and traffic information, 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 times.

- **Spontaneous (emergency/disaster) networking and peer-to-peer communications**: 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 an 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.
To measure throughput drops by walls in indoor sites, we selected three types of sites:
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 and AP-AP configuration in Figure 3.6. We did the measurement using IEEE 802.11n IEEE 802.11ac devices from three vendors to evaluate the effects of wall obstacles tow
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.
3.1.1.2 Lecture Hall Site

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

For ideal case, in order to gain the highest throughput for one-AP case, we placed AP in the middle of the room as shown in Figure 3.10. For two-AP case, we divide hosts into two groups and placed the AP in the middle of each group as shown in Figure 3.10.
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.

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.
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 11ac WiFi and 11n WiFi APs as shown in Figure 3.15 and Figure 3.16.

![Server and host for outdoor experiments in campus.](image)

**Figure 3.14: Server and host for outdoor experiments in campus.**

![IEEE 802.11ac outdoor tests.](image)

**Figure 3.15: IEEE 802.11ac outdoor tests.**

Started from 0m, the mobile host will move with 5m interval to 100m from the server station. The maximum transmission range has been fixed in 100m due to 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 dic
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 allows the user to directly communicate to an AP. However, USB WiFi devices for IEEE 802.11a, namely Buffalo WI-U2-866D[36], I-O Data WN-AC867U[37], and NEC Aterm WL900U devices from the same AP vendor were used for any experiment needed to be conducted 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) in Figure 3.17.

![USB port on a notebook PC](image)

(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 exhaust in Figure 3.17a. Heat generated from the CPU and GPU’s of the notebook can be exhausted away, towards these ventilation holes and heat up these areas [39]. Take that when we plug in the USB WiFi adapter at the USB port near these area, the device itself becomes very hot and it might exceed its standard operating environmental temperature of 0-40°C (32-104°F). In order to avoid any operating error, we selected the 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 through 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
to continue. Next, another new window will pop up, click the “OK” button again to continue the optimizing process.

The network optimizing of USB WiFi adapter (and any build-in WiFi adapter as well) be taken into consideration with condition the USB WiFi adapter using the same USB during the whole test for particular time. If the USB WiFi adapter is plugged into ano USB port, this optimizing process must be executed again in order to optimize netw 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 connect 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 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 : 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), 192.168.1 (For AP3)
- Preferred DNS server address: 192.168.11.54
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.

![Image of Manage wireless networks](image)

**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,
Bibliography


