Bachelor Thesis

Title

Access Point Selection Architecture adapted to the Real Traffic in Wireless LAN

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Abstract

According to the spread of wireless LAN, many stations (STAs) can access to the Internet via wireless LAN and therefore, availability of multiple access points (APs) will be needed for those STAs. Consequently, following significant issue arises: how to select an appropriate AP among available APs. In the existing architecture, the received signal strength is usually used to select an AP. However, such AP selection strategy causes the concentration of STAs to specific APs and STAs connect with those AP cannot use the resource of a wireless LAN effectively. Hence, the decentralized AP selection architecture for the wireless LAN have been proposed, and showed that proposed strategies can achieve an efficient and fair share of wireless access resources. So far, all performance of them are evaluated by assuming all STAs connected with the AP were engaged in greedy file transfer like FTP. But in reality, traffic patterns on Internet are widely vary. Therefore we here suggest an AP selection architecture that adapts to the real traffic in wireless LAN. In order to adapts to the real traffic, we here employed a new TCP traffic model, and evaluated performance of it.

Key words

IEEE 802.11b, Wireless Station (STA), Wireless LAN Access Point (AP), Association, Roaming, Poisson Distribution, Pareto Law
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1 Introduction

Wireless Local Area Networks (WLAN) are rapidly becoming a normal part of the communications access infrastructure. Due to their low cost, simplicity of installation and high data rates, demand for wireless LAN products has grown dramatically over the last few years, and it shows no sign of slowing. Indeed, it is strengthened by the growth of laptops and personal mobility products [1]. With the spread of wireless LAN as a way to access to the Internet, the number of stations (STAs) connected with the wireless LAN are also increasing. However, with the increase in STAs in the wireless LAN, achievable throughput per STA decreases because they share the communication resource provided by access points (APs). Therefore, multiple APs are required to serve many STAs and to improve the transmission capacity in the wireless LAN. In fact, IEEE 802.11 wireless LAN can extend the communication range by using the multiple APs.

In wireless LAN constructed with multiple APs, the following significant issue can arise: how to select an appropriate AP among available APs. In the existing architecture, the received signal strength is usually employed to select an AP. However, such AP selection strategy causes the concentration of STAs to specific APs: many STAs may associate with only a few APs because their signal strengths measured by the STAs are strong, while only a few STAs may associate with the remaining APs. This results in an imbalanced traffic load among APs in the wireless LAN.

To solve this problem, the decentralized AP selection architecture for the wireless LAN has been proposed [2, 3]. This AP selection algorithm is called Maximizing Local Throughput (MLT). In MLT, each STA first estimates its achievable throughput for each AP, and then selects the AP being expected to provide the maximum throughput. These existing
researches assumed that all STAs connected with the AP were engaged in greedy file transfer like FTP. However, as I consider the realistic traffic on Internet, short traffic patterns like HTTP are more than long traffic patterns like FTP, and traffic intervals also vary as well.

In this research, I suggest an AP selection architecture that adapts to the real traffic in wireless LAN. In order to adapt the proposed MLT algorithm to the realistic traffic, I modify the MLT algorithm in order to adapt to the realistic traffic. In my modification, each AP measure the traffic and count the active station, and tell it to the STAs.

This paper is organized as follows. Section 2 describes the overview of Wireless LAN. In section 3, I explains issues of the existing AP selection architecture, and my proposed AP selection architecture to avoid those issues is explained in section 4. Next, my simulation environment explains in section 5. In this section, new TCP traffic model and the simulation model is described in detail, and my simulation results in section 6. Finally, conclusion I made through my simulations describes in section 7.
2 Overview of Wireless LAN

Mobile computing has become extremely popular in today’s society. Today’s Internet has significant limitations, when it corresponds to the mobility. For an example, if user must be connected to the Internet through a physical cable, their movement is dramatically restricted. On the other hand, wireless connectivity poses no such restriction and allows a great deal more free movement on the part of the network users. In other words, wireless technology enables users to connect to the Internet regardless of location. As a result, wireless technologies are rapidly becoming a normal part of the communications access infrastructure. Wireless LAN is one of the widespread wireless access infrastructure in wireless technologies because Wireless LANs offer a quick and effective extension of a wired network or standard LAN. By simply installing access points to the wired network, personal computers and laptops equipped with wireless LAN cards can connect with the wired network.

2.1 Protocol Stack

Fig. 2.1 shows the relationship between the various components of the 802 family and their place in the OSI model. As shown in Fig. 2.1, 802.11 is a member of the IEEE (Institute of Electrical and Electronics Engineers) 802 family, which is a series of specifications for LAN technologies.

IEEE 802 specifications are focused on the two lowest layers of the OSI model because they incorporate both physical and data link components. All 802 networks have both a media access control (MAC) and a physical (PHY) component. The MAC is a set of rules to determine how to access the medium and send data, but the details of transmission and
reception are left to the PHY.

2.2 Types of Networks

The basic service unit of 802.11 network is the Basic Service Set (BSS), which is simply a group of STAs (STAs) that communicate with each other. Communications take place within a somewhat fuzzy area, called the basic service area, defined by the propagation characteristics of the wireless medium. When a STA is in the basic service area, it can communicate with the other members of the BSS. The BSS consists of two types of modes: the ad hoc mode and the infrastructure mode.
2.2.1 Ad Hoc Network

Fig. 2.2 shows the *ad hoc* mode network. As shown in Fig. 2.2, STAs in an *ad hoc* network communicate directly with each other and thus must be within the same communication range. The smallest possible 802.11 network is an ad hoc network with two STAs. Typically, ad hoc networks are composed by a collection of small number of STAs set up for a specific purpose and without the aid of any centralized administration or standard support services. One common use is to create a short-lived network (e.g., for a single meeting in a conference room.)

2.2.2 Infrastructure Network

Fig. 2.3 shows the *infrastructure* network. As shown in Fig. 2.3, *Infrastructure* networks are distinguished by the use of an access point from the ad hoc networks. Access points are used for all communications in infrastructure networks, including communication between
STAs and APs in the same service area. If one STA in an infrastructure BSS need to communicate with another STA in the same BSS, the communication must take two hops. First, the originating STA transfers the frame to the AP. Second, the access point transfers the frame to the corresponded STA.

In an infrastructure network, first of all the STA must have an association, which is the process for joining in 802.11 network, with an AP to obtain network service. STAs always initiate the association process, and APs may choose to accept or deny access based on the contentions of an association request.

BSSs can create a only limited coverage such as small offices and homes, but they cannot provide network coverage to large areas. Therefore, 802.11 allows wireless networks of arbitrarily large size to be created by linking BSSs into an ESS, as shown in fig. 2.4. An ESS is created by chaining BSSs together with a backbone network.

In Fig. 2.4, the ESS is the union of the two BSSs. BSSs can create a only limited
coverage such as small offices and homes, but they cannot provide network coverage to large areas. 802.11 allows wireless networks of arbitrarily large size to be created by linking BSSs into an ESS. ESS is created by chaining BSSs together with a backbone network.

2.3 802.11 Standards

The wireless LAN standards began with the 802.11 standard, developed by the IEEE in 1997. The initial base standard allowed data transmission of up to 2 Mbps. Afterward, this standard has been enhanced. These extensions are recognized by the addition of a letter to the original 802.11 standard, such as 802.11a/b/g.

The 802.11b specification was published by the IEEE in July 1999 and operates at radio frequencies in the 2.4 to 2.497 GHz bandwidth of the radio spectrum, making data speeds as high as 11 Mbps. 802.11b is fast enough to handle large e-mail attachments and run bandwidth-intensive applications like video conferencing. The 802.11a specification
was also published in July 1999, but it’s not as widely deployed as 802.11b. 802.11a employs radio frequencies between 5.15 and 5.875 GHz, making data speeds as high as 54 Mbps. The 802.11g specification was published in June 2003. While 802.11g employs radio frequencies in the 2.4 GHz to 2.497 GHz range, allowing for the throughput of up to 54 Mbps. 802.11a and 802.11g are being developed to handle increased speeds.

Channels are important to understand because they affect the overall capacity of wireless LAN. A channel represents a narrow band of radio frequency. It is important that the frequencies do not overlap and interfere in wireless LAN, thus, the channel selection which avoids the interference mutually is recommended. In Japan, the 802.11b standard has a total of 14 frequency channels. However, in order to avoid interference, it is necessary to put some channels in between them. Therefore, channel 1/6/11/14 can be used at the same time, where interference is not generated between adjoining APs. As a result, it is possible to set up four APs as maximum within the range of signals reached.

2.4 Media Access Control in MAC Layer

The 802.11 standard specifies a common medium access control (MAC) Layer, which provides various operation of 802.11-based wireless LANs. In general, the MAC Layer manages and maintains communications between 802.11 STAs by coordinating access to a shared radio channel and utilizing protocols that enhance communications over a wireless medium. Before transmitting frames, a STA must first have access to the medium, which is a radio channel that STAs share.

The coordination functions are illustrated in Fig. 2.5. Access to the wireless medium is controlled by coordination functions. In order to coordinate multiple access to the
wireless medium by multiple by multiple STAs, Ethernet-like CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) access is provided by the distributed coordination function (DCF). If contention-free service is required, it can be provided by the point coordination function (PCF) which is built on top of the DCF [4]. Contention-free services are provided only in an infrastructure network. These two important media access control techniques are described in following subsections.

2.4.1 Distributed Coordination Function (DCF)

DCF provides a standard Ethernet-like contention-based service. The DCF allows multiple independent STAs to interact without central control, and thus may be used in either ad hoc networks or infrastructure networks. The DCF is the basis of the standard CSMA/CA access mechanism. It first checks to see that the radio link is clear before transmitting. To avoid collisions, STA employs a random backoff mechanism before transmission of each frame. In some circumstances, the DCF may use the RTS/CTS clearing technique to further reduce the possibility of collisions. This section describes CSMA/CA mechanism, interframe space (IFS) and backoff control that becomes the basic technology
of DCF in detail.

• CSMA/CA

CSMA stands for Carrier Sense Multiple Access. It is a “listen before talk” scheme used to mediate the access to a transmission resource. All STAs are allowed to access the resource (multiple access) but are required to make sure the resource is not in use before transmitting (carrier sense). CSMA/CA stands for CSMA with Collision Avoidance, which is a CSMA method that tries to avoid simultaneous access (collision) by deferring access to the medium. CSMA/CA is the principle medium access mechanism employed by IEEE 802.11 Wireless LANs. IEEE 802.11 states collision avoidance method rather than collision detection method must be used, because the standard employs half duplex STAs; STAs are capable of transmission or reception, but not both simultaneously. Unlike conventional wired network, STA cannot detect a collision while transmitting in wireless LAN.

In CSMA/CA, as soon as a node receives a frame that is to be sent, it checks to be sure the medium is clear (no other node is transmitting at the time). If the channel is clear, then the packet is sent. If the channel is not clear, the node waits for a randomly chosen period of time, and then checks again to determine if the channel is clear. This period of time is called the backoff factor, and is counted down by a backoff counter. Backoff factor is determined by using IFS and backoff time which described in following sub sections. If the medium gets clear when the backoff counter reaches zero of the node, it can transmits the packet. If the packets get collided, the backoff factor is set again by doubles its’ value, and the process is repeated.
• Interframe Space (IFS)

As with traditional Ethernet, the interframe spacing plays a large role in coordinating access to the transmission medium. Priority access to the wireless medium is controlled by the IFS time period between the transmission of frames. The IFS defines the minimal time that a STA has to pass after the end of the transmission of a frame, before it may start transmitting a certain type of frame. 802.11 employs three different IFS intervals, which have been specified to provide various priority levels for access to the wireless medium; the relationship between them is shown in Fig. 2.6.

1. Short interframe space (SIFS):

The SIFS is used for the highest-priority transmissions, such as RTS/CTS frames and ACK frames. High-priority frame is transmitted once the SIFS has elapsed. Once these high-priority transmissions begin, the medium becomes busy. It guarantees the receiving STA the best possible chance of transmitting on the medium before another STA does.

2. PCF interframe space (PIFS):

The PIFS is used by the PCF during contention-free operation. STAs with
data to transmit in the contention-free period can transmit after the PIFS has expired and preempt any contention-based traffic.

3. DCF interframe space (DIFS):

The DIFS is the minimum medium idle time for contention-based services. STAs may have immediate access to the medium if it has been free for a period longer than the DIFS. The SIFS interval is shorter than a DIFS interval by two slot times. The PIFS interval shorter than the DIFS interval by one slot time. Slot time is a smallest time unit, which is predetermined by IEEE 802.11.

After the interval of SIFS, AP or STA that normally receives data, returns the ACK frame to the sender after completing the reception. SIFS is the shortest in IFS, and the ACK frame will be transmitted in top priority. Whenever the STA, which sent a data, does not receive ACK frame in response to the transmitted data frame, the STA can detect a failed transmission.

• Backoff Control

Backoff is the process by which a transmitting STA determines the time to wait before attempting to retransmit the frame, when frames collided. If all STAs waited the same length of time before retransmission, then another collision would inevitably occur. This is avoided by having each STA generate a random number which determines the length of time it must wait before testing the carrier. This time period is known as the STAs’ backoff time.

In the DCF control, STAs can acquire next transmission right when the sum of DIFS time and the backoff time becomes zero. When the data is transmitted, STAs
with a shorter backoff time can acquire an opportunity to transmit because all the
STAs use the same DIFS interval. This backoff time is decided by backoff con-
trol. The backoff control is provided by the IEEE 802.11 standard as a method for
the avoidance of the collision in addition to the carrier sense. In backoff control,
STAs of transmitting-end generate random numbers within the regulated range of
CW(Contention Window) after waiting for DIFS time, and the backoff time is de-
cided based on those values. When the frame collides unfortunately, it is possible to
decrease the probability of re-collides of frames by using of the binary exponential
backoff which double the range of CW of the backoff control for every retransmission.

2.4.2 Point Coordination Function (PCF)

PCF is an optional capacity, built on top of the DCF, which provides contention free
frame transfer with the aid of a Point Coordinator (PC). The PC, which resides in the
AP, select individual STAs for a period of time called the Contention Free Period (CFP).
For an example, the point coordinator may first poll STA-1, and STA-1 can transmit data
frames during a specific period of time, and no other STAs can send anything. The point
coordinator will then poll the next STA and continue down the polling list, while letting
each STA to have a chance to send data. Polling list managed on the AP, which records
whether the STAs are active or not.

Thus, PCF is a contention-free protocol and enables STAs to transmit data frames
synchronously, with regular time delays between data frame transmissions. This makes
it possible to more effectively support real time traffic flows, such as video and control
mechanisms, having stiffer synchronization requirements.
2.5 Hidden Terminal Problem

Ethernet contains the signals and distributes them to network nodes. Wireless networks have fuzzy boundaries, sometimes to the point where each node may not be able to communicate with every other node in the wireless network. Sometimes, STAs in the same BSS cannot recognize each other due to influence of an obstacle, which is impenetrable by signals. Because of that, wireless signals cannot reach each other. This phenomenon is known as hidden terminal problem.

In the Fig. 2.7, STA-1 can communicate with STA-2, but a barrier something prevents STA-1 and STA-2 from communicating directly with STA-3. From the perspective of STA-1 and STA-2, STA-3 is a ‘hidden’ STA. In above figure, STA-1, 3 and STA-2, 3 are impossible to do carrier sense and cannot get a correct understanding about status of use of a channels due to the barrier. As a result, frames collide at the AP, when STA-1 and STA-3 communicate at the same time. In this case, collision detection does not work.
correctly and it leads to the reduction of the throughput.

2.5.1 RTS/CTS Procedure

Collisions caused by hidden nodes may be hard to detect in wireless networks, because wireless STAs are generally half-duplex; they don’t transmit and receive at the same time. To prevent collisions, 802.11 allows STAs to use Request to Send (RTS) and Clear to Send (CTS) frames.

Fig. 2.8 illustrates the RTS/CTS procedure. When STA-1 has a frame to send, it initiates the process by sending a RTS frame. The RTS frame serves several purposes: in addition to reserving the wireless link for transmission, stopping to send data by another STAs. If the target STA receives RTS, it responds with CTS. Like the RTS frame, the CTS frame silences STAs in the immediate vicinity. Once the RTS/CTS exchange is complete, STA-1 can transmit its frames without interference by any hidden nodes. On the other hand, hidden nodes beyond the range of the sending STA are silenced by the CTS from the receiver. When the RTS/CTS clearing procedure is employed, any frames must be

![Fig. 2.8: RTS/CTS clearing procedure](image-url)
positively acknowledged.

\subsection{Network Allocation Vector (NAV)}

Carrier sensing is used to determine if the medium is available. Two types of carrier sensing functions in 802.11 manage this process: the physical carrier-sensing and virtual carrier sensing functions. Physical carrier-sensing functions are provided by the physical layer and depend on the medium and modulation used. Virtual carrier-sensing is provided by the Network Allocation Vector (NAV). Most 802.11 frames carry a duration field, which reserve the medium for a fixed time period.

The NAV is a timer that indicates the amount of time the medium will be reserved. STAs set the NAV to the time for which they expect to use the medium, including any frames necessary to complete the current operation. Other STAs count down from the NAV to zero. When the NAV is nonzero, the virtual carrier-sensing function indicates that the medium is busy; when the NAV reaches zero, the virtual carrier-sensing function indicates that the medium is idle. Fig. 2.9 shows how the NAV avoids interruption.
In Fig. 2.9, the NAV is carried in the frame headers on the RTS and CTS frames; it is depicted on its own line to show how the NAV relates to actual transmission in the air. To ensure that the sequence is not interrupted, STA-1 sets the NAV in its RTS to block access to the medium while the RTS is being transmitted. All STAs that hear the RTS defer access to the medium until the NAV expires.

RTS frames are not necessarily heard by every STA in the network. Therefore, the recipient of the intended transmission responds with a CTS that includes a shorter NAV. CTS has a shorter NAV than RTS in order to expire the NAV of both RTS and CTS at the same time. This NAV prevents other STAs from accessing the medium until the transmission gets complete. After completing the process, the medium can be used by any STA after distributed interframe space (DIFS), which is depicted by the CW. RTS/CTS exchanges may be useful in crowded areas with multiple overlapping networks.

2.6 Access Procedures to an existing BSS

When a STA wants to access an existing BSS, the STA needs to get synchronized information from the AP or from the other STAs. The STA can get its information by one of following two methods [5]. Those two methods are valid, and either one can be chosen according to the power consumption/performance trade off.

1. Passive Scanning:

Passive scanning involves only listening to IEEE 802.11 traffic. In the passive scanning procedure, STA moves from channel to channel and records the information from all Beacon Frames (it is a periodic frame sent by the AP with synchronization information) it receives from the AP. At the conclusion of the passive scan, which
may involve listening to one or more channels, STA has accumulated information about the BSSs in its vicinity.

2. Active Scanning:

Active scanning requires the scanning STA to transmit and receive responses from APs. In an active scan, STA will check every channel by sending Probe Request frame. If there is a BSS on the channel that matches the Service Set Identifier (SSID), which is a 32-character unique identifier attached to the header of frames sent over a WLAN that acts as a password when a mobile device tries to connect to the BSS, the AP in that BSS will respond by sending a Probe Response frame to the scanning STA. Once the scanning STA has processed any responses, or has decided there will be no responses, it may change to another channel and repeat the process. At the conclusion of the scan, STA has accumulated information about the BSSs in its vicinity.

2.6.1 The Authentication Procedure

Once the STA has found an AP, and decided to join its BSS, it will go through the authentication process, which is the interchange of information between the AP and the STA, where each side proves a given password. 802.11 does not restrict authentication to any particular scenario. Any STA can authenticate with any other STA. In practice, authentication is most useful in infrastructure networks. 802.1x and 802.11i are well-known standards available for authentication in wireless LAN. 802.1x provides an authentication framework for wireless LANs, allowing a user to be authenticated by a central authority.
2.6.2 The Association Procedure

When the STA is authenticated, then it will start the association process, which is the exchange of information about the STAs and BSS capabilities, and which allows the set of APs to know about the current position of the STA. Only after the association process is completed, a STA is capable of transmitting and receiving data frames.

2.6.3 Roaming

Roaming is the process of moving STAs from one cell (or BSS) to another without interrupting connection. The 802.11 standard does not define how should the roaming be performed, but defines the basic tools for that. It includes the active/passive scanning and a re-association process, where a STA which is roaming from one AP to another will become associated with the new one.
3 Access Point Selection Architecture

In this section, the existing access point selection architecture will be explained first, and then I clarify issues of the existing selection architecture. Next, I describes the decentralized AP selection architecture for the wireless LAN proposed in [2] and [3]. Dynamic AP selection mechanism is described subsequently, which executes an AP selection algorithm periodically while connecting stations to AP.

3.1 Current Situation of Wireless LAN and Issues

In practice, an effective throughput of IEEE 802.11b is in the range of $4 \sim 5 \text{ Mb/s}$ due to influence of the MAC control of CSMA/CA and the overhead by the wireless frames. STAs share the communication resource provided by AP. Therefore with the increase in the number of STAs connect to an AP, throughput of each STA degrades. As a result, the number of STAs that can be accommodate with an AP is in the range of $10 \sim 20$, so that multiple APs need to be set up within the wireless LAN in order to increase the number of STAs. In addition, in the case of IEEE 802.11b, when the multiple APs are set up in the vicinity without interference, it is possible to install four APs as maximum as described in section 2.3.

How to select an appropriate AP among available APs is becoming very important issue, when the multiple APs exist in the wireless LAN. In the existing architecture, each STA uses the received signal strength to select an AP. However, such AP selection strategy causes the concentration of STAs to specific APs: many STAs may associate with only a few APs because their signal strengths measured by the STAs are strong, while only a few STAs may associate with the remaining APs. This results in an imbalanced traffic load on
APs in the wireless LAN, thereby degrading the fairness in STA throughput and harming of efficient use of the wireless LAN resource.

In order to solve this issue, decentralized AP selection architecture has been proposed in [2] and [3]. In the proposed decentralized architecture, each STA selects its AP based upon the algorithm which optimizes its own throughput locally. Furthermore, each STA dynamically changes its associating AP in response to changing wireless condition. Following section describes the proposed decentralized architecture.

3.2 Analysis of Throughput in MLT

In the proposed algorithm, each STA first estimates its achievable throughput for each AP, and then selects the AP which expects to provide the maximum throughput. Namely each of the STAs tries to optimize its own throughput locally, so that this algorithm is referred to in short as MLT (Maximizing Local Throughput). Figure 3.1 shows the packet sending sequence in IEEE 802.11b.

Fig. 3.1: packet sending sequence in IEEE 802.11b
As shown in Fig. 3.1, transmission time $t_T$ spent to transmit a packet of Data [bits] is given by the equation 3.1.

$$t_T = RTS + CTS + \frac{Data (bits)}{Rate (b/s)} + ACK + DIFS + 3SIFS \quad (3.1)$$

Equation 3.2 shows the average transmission time $T_w$ which is required for sending and receiving a packet correctly.

$$T_w = t_T + \sum_{i=1}^{\infty} P_i \cdot (1 - P) \cdot i \cdot t_T = \frac{t_T}{1 - P} \quad (3.2)$$

In this equation, $P$ is defined as the PER (Packet Error Rate) in order to take into account of the wireless link condition between STA and AP. Consequently, the throughput of the AP can be given by the equation 3.3.

$$\theta = \frac{Data}{T_w} = \frac{Data \cdot (1 - P)}{t_T} \quad (3.3)$$

With the assumption of the ideal case in which the probability of collision can be negligible, STAs that communicate with an AP can evenly share the wireless access resources, so that the throughput of the STA $\theta$ will be given by the following equation.

$$\theta = \frac{Data \cdot (1 - P)}{t_T \cdot N} \quad (3.4)$$

In this equation, $N$ indicates the number of STAs associating to the AP. Equation 3.4 simply depends on the following weighted function for each AP when packet size and $t_T$ is constant.

$$W_{MLT} = \frac{1 - P}{N} \quad (3.5)$$

Where, $P$ denotes the PER, which can be obtained from the received signal strength, and $N$ denotes the number of STAs which currently communicate with the AP. In the
case of IEEE 802.11b, retransmission process is done, even if there is 1 bit error in the received frame. As a result, when $P_e$ is defined as the BER (Bit Error Rate), PER can be expressed as $P = 1 - (1 - P_e)^{PacketSize}$. BER can be obtained from the received power. Therefore, in order to provide each STA with the additional information of $N$ and PER, APs should be slightly modified to inform the additional information on the Probe Response and Beacon frames. Finally, STA selects the AP with the largest $W_{MLT}$.

3.3 Dynamic AP Selection Mechanism

First, each STA independently selects an appropriate AP according to the algorithm described previously when finding a wireless LAN. Then, the AP selected first may become an inappropriate one for the STA because the condition of wireless LAN changes continuously. Therefore, a new mechanism is necessary to cope with the change in the condition of the wireless LAN. Figure 3.2 shows the proposed dynamic selection mechanism in [2] and [3].

As described in Fig. 3.2, the dynamic selection mechanism has three states: search state, re-search state, and idle state. In the search state, a STA executes the proposed algorithm to predict the throughput of all available APs at predetermined intervals, denoted by
Search Interval (SI). However the STA does not immediately roam, but transits to the next re-search state if some other different AP is selected as an appropriate AP. In the re-search state, the STA re-executes the algorithm after some backoff time and will roam only if the AP selected in the search state is expected to achieve the maximum throughput again. After roaming to the new AP, STA transits to idle state. In the idle state, STA does not calculate the weighted function to any of the AP available.

The dynamic selection mechanism is more precisely described as follows; each of the numbers on the Fig. 3.2 corresponds to the number of items below.

1. A STA has associated to an appropriate AP, it calculates the weighted function of available APs according to the algorithm of MLT at the interval of SI.

2. If new AP, denoted by $AP_{\text{new}}$, is selected as an appropriate one, as a result of calculation of weighted function, STA transits to re-search state and re-calculates the weighted function after $Backoff Time$ that is determined by random variable in $[0, 1]$.

3. If the $AP_{\text{new}}$ is selected as an appropriate AP again after re-calculation, the STA actually roams to the $AP_{\text{new}}$, and transits to idle state.

4. If the current AP is selected after re-calculation, STA returns to the search state.

5. If some other AP is selected, which is different from both the current one and the $AP_{\text{new}}$, STA remains the re-search state. The newly selected AP is regarded as $AP_{\text{new}}$, and the STA re-calculates the weighted function after $Backoff Time$.

6. After roaming to the new AP, STA waits for the Idle Time (IT) in order to prevent the ping-pong effect, and returns to the search state.
4 Proposed Algorithm

In this section, I explain the way of counting the active STAs, which are actually communicating with an AP.

In my simulation, MLT is employed as the AP selection architecture. As described in section 3.3, in MLT algorithm, each STA derives the values of $W_{MLT}$ obtained by the equation 3.5 for all APs, and the AP with the largest $W_{MLT}$ will be selected as an appropriate AP.

In existing researches, they assumed $N$ in the equation 3.5 as the number of STAs that is being associated with AP. But that kind of assumption cannot be made in the place like a meeting in reality, where, all STAs are not always communicating while connecting it with an AP. Therefore, it is very important to estimate the value of $N$ which reflects the number of active STAs connecting with the AP correctly in order to adapt the MLT mechanism to real traffic. In the following paragraph, I describes how to estimate $N$ correctly which is the viewpoint of this study.

Fig. 4.1: Estimate of N
In Fig. 4.1, STA1 and STA2 are communicating with the AP. In this figure a frame from STA1 reaches to AP at time $y$, and frames from STA2 reach to AP at time $x$ and time $z$. At the AP, all those reception times are recorded which corresponds to each frame from all STAs. So that, as the time being, AP holds a list of all STAs which communicated with it and corresponded time of communication. An AP estimates the correct $N$ at each time interval. When I count the number of an active STAs which correspond to the current time, I see the number of active STAs communicating with an AP are in the interval of time history, and take it as $N$. For an example, a frame from the STA2 has reached to the AP at time $z$ in the above figure. Because of the time $z$ is in the interval of time history from Now, AP takes STA2 as an active STA.
5 Simulation Environment

In this section, a simulation model and a traffic model employed here are explained. Then, I describe how to locate APs in the simulation model, and proposed algorithm. Finally, I explain the simulation scenarios that I execute.

5.1 Simulation Model

Simulation model is illustrated in Fig. 5.1; a source (fixed host) communicates with 40 STAs via four APs. Simulation parameters are described in Tab. 5.1.

Each AP operates at a data rate of 11 Mb/s on different channels to prevent the interference among the APs. Simulation experiments were performed by using the network
The TCP variant employed here is TCP with SACK option, and its packet size is of 1,500 bytes as mentioned in Tab. 5.1. Furthermore, it is assumed that TCP traffic act up to following two steps.

1. Communication intervals of TCP flow correspond to the *Exponential distribution*.

2. Size of the file forwarded through TCP flow corresponds to the *Pareto law*.

The wired link between *Source* and *Switch* is 100 Mb/s in bandwidth and 10 µsec in propagation delay, similarly the wired link between *Switch* and each AP is 100 Mb/s in bandwidth and 1 µsec in propagation delay.
5.2 Traffic Model

TCP traffic described above, can be illustrated as in Fig. 5.2. The average value of TCP file size is set to the average value of UNIX file size, namely 22 KByte. The probability distribution function of the TCP file size can be expressed as equation follows.

\[ P[X \leq x] = 1 - \left( \frac{k}{x} \right)^{\alpha} \quad 0 < \alpha, 0 < k \leq x \]  

(5.1)

In equation 5.1, \( k \) indicates the minimum value that can be gained by the random variable. \( \alpha \) is the shape parameter of the Pareto distribution. When the value of parameter \( \alpha \) is small, deviation of the resulting value grows with the execution of each simulation. In other words, when the file size follows pareto distribution with small \( \alpha \), it grows the probability of generating of small files [6]. In the simulation, value of \( \alpha \) is set to 1.294, and the average communication interval, which is the interval between some data transmission, is set to 3.2 sec. This is the average interval of the OFF time in Fig. 5.2. Concerning these values, investigation has already done, and has proven as an appropriate values [6].

5.3 Topology

Each AP is located as shown in Fig. 5.3. As mentioned previously, many STAs can connect with some specific AP and imbalance of traffic load will thus happen among APs in reality. To simulate of this feature, STAs are located uniformly in a rectangular area
of 30m by 30m, which provides most biased situations in terms of STAs’ geographical location mentioned in [2, 3]. Arrivals of STAs are uniformly distributed over a period of 10 [sec]. After all of 40 STAs are located within the Wireless LAN, I assume that no movements of them occurs during the simulation.

In addition, other parameters of the dynamic AP selection mechanism which is recommended as best values in [2] are used in simulations, and they are shown in Tab. 5.2. In this table, SI, BT, IT are described in the dynamic AP selection mechanism.

![Arrangement of APs](image)

Fig. 5.3: Arrangement of APs
Tab. 5.2: Status Transition Parameters of Existing MLT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI (Search Interval)</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>BT (Backoff Time)</td>
<td>0 ~ 1.0 sec</td>
</tr>
<tr>
<td>IT (Idle Time)</td>
<td>3.0 sec</td>
</tr>
</tbody>
</table>

To quantify the performance, I employ the throughput and the distribution of the average throughput as performance measure. In addition, I also use the balance index $\beta$ to reflect some fairness. Suppose $B_i$ is the average throughput of $STA_i$, then I define the balance index $\beta$ to be:

$$
\beta = \frac{\left(\sum B_i\right)^2}{N \times \sum (B_i)^2} \tag{5.2}
$$

Where $N$ is the total number of STAs allocated in the simulation. The balance index has the property that it takes 1 when all STAs have exactly the same throughput and it gets closer to $\frac{1}{N}$ when throughput of STAs are heavily imbalance.

Tab. 5.3 shows the status parameters of proposed algorithm. In my simulation, these two blocks of parameters are used respectively.

Tab. 5.3: Status Parameters of Proposed Algorithm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>10.0 sec</td>
</tr>
<tr>
<td>BT</td>
<td>5.0 sec</td>
</tr>
<tr>
<td>IT</td>
<td>5.0 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>BT</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>IT</td>
<td>3.0 sec</td>
</tr>
</tbody>
</table>
5.4 Simulation Scenario

In my simulation, the minimum, average and maximum throughput of each STA and total throughput of all STAs is evaluated through simulation experiments. My simulation scenarios using TCP traffic model is described below.

step 1: Evaluate the performance of the existing MLT mechanism which considers $N$ as the number of STAs being associated with the AP during all the simulation time.

step 2: Count the number of STAs being communicated with the AP by concerning the communication history from $0.1 \sim 0.7 \, [sec]$ in the past, when the announcing interval of $N$ assumed to be constant.

step 3: Evaluate the case where the announcing interval changed from $1 \sim 4 \, [sec]$ concerning step 2.
6 Simulation Result

In this section, we show my simulation results, which are done in the three steps explained in section 5.4. Simulation time is set to 180 [sec]. TCP packets are generated at the time, which corresponding to the Exponential distribution.

6.1 Performance of Existing MLT Mechanism on a new Traffic Model

As mentioned before, we first evaluate the performance of the existing MLT mechanism on the TCP traffic model described in section 4.2. As depicted in Fig. 5.2, the traffic model has ON and OFF times and each data transmission is completed only in ON time. I distinguished ON time and OFF time of the traffic model by concerning the number of ACK produced in the transmission process. If ACK has produced, we consider that time as ON time. I here use the total throughput, which is the sum of the throughput of all the 40 STAs in the entire simulation time (ON + OFF time), minimum, average and maximum throughput only in ON time to examined for the characteristic of throughput performance.

6.1.1 Throughput Performance: Entire simulation time Vs ON time

Figure 6.1 illustrates the total throughput of 40 STAs as a function of time, which is plotted in every 0.1 [sec]. As described above, the total throughput is calculated by considering the entire simulation time.

In this case, the total throughput of all the 40 STAs in entire simulation time (ON + OFF time) becomes 19.76 Mb/s. Next, I show an average throughput that can be obtained by each STA. Figure 6.2 illustrates the average throughput of each STA. In this case, the
entire simulation time is also considered when calculating the throughput. Table 6.1 shows the minimum, average and maximum throughput of 40 STAs.

Next, I mainly consider the performance of STAs in only ON time of the TCP traffic model illustrated in Fig. 5.2. Figure 6.3 shows the average throughput that can be achieved for each STA in ON time. As you can see in the Fig. 6.3, an average throughput is

Tab. 6.1: Throughput in Entire simulation time(ON+OFF Time)

<table>
<thead>
<tr>
<th>Throughput [Mb/s]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.367</td>
</tr>
<tr>
<td>Average</td>
<td>0.491</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.811</td>
</tr>
</tbody>
</table>
Fig. 6.2: Throughput of each STA at the entire simulation time

Fig. 6.3: Average Achievable Throughput of Existing MLT
Tab. 6.2: Throughput in ON Time

<table>
<thead>
<tr>
<th>Throughput [Mb/s]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.90</td>
</tr>
<tr>
<td>Average</td>
<td>2.30</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.21</td>
</tr>
</tbody>
</table>

fluctuating in the range of 1.88 \( \text{Mb/s} \) and 2.69 \( \text{Mb/s} \). An average throughput of each STA, which is calculated concerning only ON time is much higher than that of the entire simulation time as shown in Fig. 6.2. Table 6.2 shows the minimum, average and maximum throughput of 40 STAs. It is clearly demonstrated that the throughput of the STA in ON time is dominant in the entire simulation time.

6.1.2 Probability Density Function

In this section, I examine the fairness in the throughput achieved by each of STAs by investigating both the distribution of average throughput and balance index. Figure 6.4 illustrates the probability density function of an average throughput in ON time. Probability is calculated by counting the number of STAs out of all 40 STAs which are in the 100 \( Kb/s \) interval. As you can see in Fig. 6.4, the greater part of STA has concentrated in the throughput range of 2.1 \( Mb/s \) and 2.5 \( Mb/s \).

Furthermore, the balance index is 0.994. This value is very closer to 1, and therefore I can remark that MLT can achieve a high fairness in STA throughput even when STAs are unevenly distributed.

Figure 6.5 illustrates the cumulative distribution function of an average throughput in
Fig. 6.4: Probability Density Function of Existing MLT

Fig. 6.5: Cumulative Distribution Function
ON time, which corresponds to Fig. 6.4. As can be seen in Fig. 6.5, 50% of STAs achieve a throughput of more than 2.25 Mb/s.

### 6.1.3 Active Stations

I here consider a STA to be active when it transmits at least a packet. Fig. 6.6 shows the change in number of active STAs as a function of time. On the other hand, Tab. 6.3 shows the average number of STAs associate with each AP. From Fig. 6.6, the average number of active STAs becomes 8.35, whereas the average number of STAs associate with AP1 and AP2 is higher than that.

Next, I compare the ideal average throughput with that of the simulation results. I assume the ideal average throughput of one AP to be 5.5 Mb/s. As shown in Fig. 5.3, I used the topology of four APs, and therefore the ideal average throughput for all four

![Fig. 6.6: Active STAs](image-url)
Tab. 6.3: Average number of STAs associate with each AP

<table>
<thead>
<tr>
<th></th>
<th>AP1</th>
<th>AP2</th>
<th>AP3</th>
<th>AP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA (Avg)</td>
<td>12.9</td>
<td>12.8</td>
<td>7.1</td>
<td>6.9</td>
</tr>
</tbody>
</table>

APs becomes 22 \(Mb/s\). Hence, the ideal total average throughput of a STA becomes 2.63 \(Mb/s\). An average throughput I achieved in ON time was 2.30 \(Mb/s\). Therefore, when I consider only ON time in the traffic model in Fig. 5.2, I can attain 87.29\% of the ideal throughput.

From the above results, it is much clear from Fig. 6.6, only 50 \% of the STA out of 40 STAs or less than that is being active at a time. Therefore, \(N\) should be evaluated accurately in order to achieve a high throughput.
6.2 Performance of the Proposed Algorithm

In this section, I evaluate the performance of the newly proposed algorithm which consider \( N \) of the equation 3.5 as the number of STAs actually being communicating with an AP. In my simulation experiments, I adopt two blocks of parameters described in Tab. 5.3. Here I evaluate the optimum values of the following two parameters.

(1) How much communication history in the past should be considered to presume the number of STAs being actually communicating.

(2) How often the number of STAs being actually communicating should be announced by AP to STA.

Consequently, in the simulations my objective is to determine the best value of them. First, I execute simulations with the settings of status parameters of the dynamic AP selection mechanism as follows.

- Search Interval (SI) is set to 10 [sec].
- Backoff Time (BT) is set to 5 [sec].
- Idle Time (IT) is set to 5 [sec]

In Tab. 6.4 ~ 6.7, ”Time History” is referred to communication history of above (1). ”Interval” is referred to an interval of announcing the information of above (2). Table 6.4 and 6.5 shows the minimum, average and maximum throughput of all 40 STAs in ON time which Interval time from 1 to 4 [sec]. Next I changed the values of status parameters as below, and performed the simulation.

- Search Interval (SI) is set to 3 [sec].
- Backoff Time (BT) is set to 3 [sec].
- Idle Time (IT) is set to 3 \( [sec] \)

Tab. 6.6 and Tab. 6.7 shows the minimum, average and maximum throughput of all 40 STAs in ON time.

As you can see in Tab. 6.4 \( \sim 6.7 \), a high throughput is obtained in all cases. The higher value of the average throughput can be gained, when the communication history at 0.1 [sec] and the announcing interval at 2 [sec] in Tab. 6.4. In this case, an average throughput becomes 2.58 \( Mb/s \). Here, I describe the throughput characteristic related to this case. Fig. 6.7 shows the average achievable throughput that can be achieved for each STA in the above case (Interval: 2 sec, Time History: 0.1 sec). As you can see in the Fig. 6.7, an average throughput is fluctuating in the range of 2.23 \( Mb/s \) to 2.89 \( Mb/s \).

When I compare the average throughput of 2.58 \( Mb/s \) in Tab. 6.4 with the average throughput in the Tab. 6.2, it can be seen that a throughput is improved by considering the number of STAs actually being communicating with AP as \( N \) of the equation 3.5. I can attain 97.92\% of the ideal throughput (2.63 \( Mb/s \)) in this case. Consequently, I can say more than 10\% of the ideal throughput is improved by employing the newly proposed

<table>
<thead>
<tr>
<th>Interval (sec)</th>
<th>Throughput [Mb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time History (sec)</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.63</td>
</tr>
<tr>
<td>Average</td>
<td>2.55</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.26</td>
</tr>
</tbody>
</table>
Tab. 6.5: Throughput Characteristic-2 (SI=10 sec, BT=5 sec, IT=5 sec)

<table>
<thead>
<tr>
<th>Interval (sec)</th>
<th>Throughput [Mb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Time History (sec)</td>
<td>0.1 0.3 0.5 0.7</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.51 1.13 1.32 1.08</td>
</tr>
<tr>
<td>Average</td>
<td>2.49 2.45 2.51 2.52</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.24 3.21 3.28 3.25</td>
</tr>
</tbody>
</table>

Tab. 6.6: Throughput Characteristic-1 (SI=3 sec, BT=3 sec, IT=3 sec)

<table>
<thead>
<tr>
<th>Interval (sec)</th>
<th>Throughput [Mb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Time History (sec)</td>
<td>0.1 0.3 0.5 0.7</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.35 1.30 1.09 1.27</td>
</tr>
<tr>
<td>Average</td>
<td>2.51 2.46 2.23 2.45</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.26 3.25 2.95 3.20</td>
</tr>
</tbody>
</table>

Tab. 6.7: Throughput Characteristic-2 (SI=3 sec, BT=3 sec, IT=3 sec)

<table>
<thead>
<tr>
<th>Interval (sec)</th>
<th>Throughput [Mb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Time History (sec)</td>
<td>0.1 0.3 0.5 0.7</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.39 1.20 1.34 1.12</td>
</tr>
<tr>
<td>Average</td>
<td>2.44 2.47 2.46 2.44</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.23 3.26 3.25 3.23</td>
</tr>
</tbody>
</table>
algorithm when comparing to existing MLT.

Fig. 6.8 illustrates the probability density function of an average throughput in ON time under the proposed algorithm. Probability is calculated by counting the number of STAs out of all 40 STAs which are in the interval of a throughput of 50 Kb/s. As you can see in Fig. 6.8, the greater part of STA has concentrated in the throughput between 2.45 Mb/s and 2.8 Mb/s. With the use of the proposed algorithm, the balance index becomes 0.996. When I compare the Fig. 6.8 with the Fig. 6.4, it is obvious that greater part of STAs can gain a high throughput with the proposed algorithm and much more fairness in STA throughput than the existing MLT.

Next I focus on a minimum throughput under the proposed algorithm. Proposed scheme achieve a minimum throughput of 1.49 Mb/s, about 1.65 times that of existing MLT (0.90 Mb/s). This is because the AP can measure the active number of STAs correctly, thus, STAs can select the appropriate AP with the highest $W_{MLT}$ in equation 3.5.

Fig. 6.9 and 6.10 shows the number of active STAs from the view of each AP as a function of time. Here I calculated the number of active STAs by paying attention on the communication history and the announcing interval with the values of 0.1 [sec] and 2 [sec] respectively. It can be seen from the Fig. 6.9 and 6.10 that, the number of active STAs of AP1 and AP2 is nearly twice than that of AP3 and AP4. Reason for this behavior is all 40 STAs are located within the area which provides a most biased situation in Fig. 5.3, and therefore majority of STAs concentrate with AP1 and AP2. Furthermore, number of active STAs are varied intensively. Even the number of STAs being associated with AP is constant as shown in Tab. 6.3, the number of STAs actually communicating is varied like in Fig. 6.9 and 6.10. Therefore, a high throughput can be gain by considering N as the
Fig. 6.7: Average Achievable Throughput of Proposed Algorithm

Fig. 6.8: Probability Density Function of Proposed Algorithm
number of STAs in Fig. 6.9 and 6.10.

I showed through my simulation experiments that, proposed scheme can improve both a minimum and average throughput compare to existing MLT, and furthermore I could obtain a high fairness in STA throughput.
Fig. 6.9: Active STAs of AP1 and AP2

Fig. 6.10: Active STAs of AP3 and AP4
7 Conclusion

According to the spread of wireless LAN, many stations (STAs) can be access to the Internet via wireless LAN and therefore, availability of multiple access points (APs) will be needed for those STAs. The issue of selecting the best AP for the STA becomes very important in wireless LAN with multiple APs. In order to resolve this issue, MLT algorithm has been proposed [2, 3], and showed that it can achieve an efficient and fair share of wireless access resources between STAs. However, existing MLT algorithm cannot be adapted to the realistic traffic, because they assumed that all STAs connected with the AP were engaged in greedy file transfer like FTP.

In this paper, I extended the MLT algorithm to be able to adapt to the real traffic in wireless LAN to determine \( N \) by evaluating the number of STAs actually communicating with an AP. First, I introduced a new TCP traffic model and executed the performance evaluation under the existing MLT algorithm. As a result I could obtain a high throughput and fairness in STA throughput. Next, I investigated the performance of our proposed scheme.

Through simulation experiments, I have shown that the proposed algorithm significantly improves both throughput and fairness in STA throughput compared with the existing MLT. I could improve the throughput by more than 10% of the ideal throughput by evaluating the appropriate \( N \). I showed best value of the average throughput of STA can be achieved with the parameters SI, BT, IT of 10 [sec], 5 [sec] and 5 [sec] respectively. From these results, I have shown that it is necessary to take the communication history and announcing interval short in order to improve the throughput, and the optimum values for communication history and announcing interval are 0.1 [sec] and 2 [sec] respectively.
Furthermore, I focused on the improvement of an achievable minimum throughput. I was able to improve it by 60.4%. This is because the AP can measure the active number of STAs correctly, thus, STAs can select the appropriate AP with the highest $W_{MLT}$. Therefore, I can remark that newly our extension of MLT algorithm is recommended from a viewpoint of its throughput performance and its fairness in the throughput.
Acknowledgement

Many people supported me during the completion of this thesis with criticism, helpful assistance and references. This thesis would have never been possible without them.

First of all I would like to thank Professor Yuji Oie for his guidance and encouragement. He was a wonderful supervisor whose assistance and motivation were greatly appreciated.

I wish to express my sincere gratitude to Yutaka Fukuda, who guided this work and helped whenever I was in need.

I am grateful to the members of Oie laboratory for their support and their comradeship.

Finally, I would like to express my deepest gratitude for the constant support, understanding and love that I received from my girl friend and my parents.

I dedicate this thesis to my mother and father.
Reference


