國 立 交 通 大 學

電信工程學系

硕 士 論 文

IEEE 802.11/802.16e 無線區域及都會型異質性網路之換手性能分析

On the Handoff Performance of the Hybrid IEEE 802.11 Wireless Local Area Network and 802.16e Mobile WiMax System

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摘　　　要

近年來，透過 IEEE 802.11 無線區域網路(wireless local area networks, WLANs)上網已經是相當的普遍，但是多數應用被限制在沒有換手機制的無線網路內，當很多即時應用快速發展，如 VoIP(Voice on IP)等，如何有效降低無線網路換手延遲時間變成是一個很重要的換手議題；另外，近來 IEEE 802.16e 無線都會網路(wireless metropolitan area networks, WMANs) 也吸引到很大的關注，因此，相信在未來，IEEE 802.16e 無線都會網路將會結合現有的 IEEE 802.11 無線區域網路形成一個混合型無線網路，無庸置疑的，智慧型無間隙換手在這樣的混合型網路將會變成一個很重要的議題。

在這篇論文中，我們首先研究 IEEE 802.11 無線區域網路的換手問題，從相關換手延遲時間量測的文獻中，發現其中搜尋可用的 IEEE 802.11 基地台(Access point)的延遲佔了換手絕大部份時間，因此，我們首先提出一個 IEEE 802.11 換手機制中搜尋基地台所需時間及其成功率的分析模型，我們並發現兩個很重要的設計參數(探測需求封包(probe request frame)及探測回覆封包(probe response frame)的傳送次數)會影響搜尋基地台所需的時間，我們進一步提出最佳化這兩個換手設計參數的演算法，我們的分析結果指出，比起現有標準定義的方法，當一個系統使用最佳探測需求封包(probe request frame)及探測回覆封包(probe response frame)的傳送次數時，可降低 30%到 40%的有效搜尋時間。

在 IEEE 802.11/802.16e 無線區域及都會異質性網路之換手問題中，當有兩個系統同時作換手時，有比較短換手時間的系統不一定會有比較高的資料吞吐量，因此，我們針對一個新的換手情境‘‘WLAN to hybrid WLAN/WiMax’’，提出同時考慮跨系統(vertical)及同系統(horizontal)換手的動態網路選擇機制去決定連線的網路，在提出的機制中，我們要求使用者等一個最大網路選擇時間以至於可以最大化可傳輸的資料量，另外，我們亦提出飽和網路選擇時間去最佳化傳輸資料量及換手時間的所形成的擇衷(trade-off)問題。經過我們的分析結果指出，當鄰近無線網路有 5~25 個使用者時，使用我們提出的機制可以提昇至少 10%的平均資料傳輸量。

On the Handoff Performance of the Hybrid IEEE 802.11 Wireless Local Area Network and 802.16e Mobile WiMax System

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ABSTRACT

In recent years, the IEEE 802.11 wireless local area networks (WLANs) have become very popular. However, most application scenarios are limited to hot spot areas without handoff. As many real-time application, e.g. voice over IP(VoIP) grow rapidly, one of the burning issues for WLAN is to reduce handoff latency. Furthermore, IEEE 802.16e wireless metropolitan area networks(WMAN) also attract a great deal of attentions. Thus, in the future, we can expect the appearance of the hybrid IEEE 802.11 WLANs and IEEE 802.16e WMANs system. Clearly seamless and smart handoff in this hybrid network will become an increasingly important issue.

In this thesis, we first investigate the handoff issue for the IEEE 802.11 WLANs. Some studies have indicated that the latency in searching available channel in neighboring AP dominates handoff latency. Therefore, we develop an analytical model to calculate the channel search latency and its success probability for the IEEE 802.11 WLANs. We find that the number of the probe requests and that of probe responses are two key design parameters influencing handoff channel search time. Thus, we develop a method to determine the optimal numbers of probe request and probe response. The numerical results demonstrate that a system with the optimum probe request and probe response can reduce the effective search time by 30% to 40% compared to the legacy IEEE 802.11 WLANs.

As for the handoff issue in the hybrid IEEE 802.11 WLANs and IEEE 802.16e WMANs system, the system which has shortest handoff latency may not have the highest throughput. Thus, we develop a dynamic network selection scheme to determine the connecting system in a new ``WLAN to hybrid WLAN/WiMax'' handoff scenario, in which we consider both the vertical and horizontal handoffs. The proposed scheme requests the station to wait an additional network selection time ``t_w'' before the selection to maximize the amount of delivered bits during a dwelling

time. We formulate an optimization problem to find the maximum network selection time for maximizing the delivered information bits. In addition, we also find the saturation network selection time for optimizing the delivered bits and handoff latency during the dwelling time. From the numerical analysis, in the case with 5~25 stations in target WLAN, the proposed scheme can improve the delivered bits at least by 10% compared to that without awaiting the scenario.

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CHAPTER 1

Introduction

As the rapid progress of communication techniques in recent years, various wireless networks have been widely deployed. One can imagine that the future wireless access network will consist of wireless networks with different available data rate and coverage range. For example, the IEEE 802.11 wireless local area network (WLAN) can provide high per user data rate and low deployment cost [2,3]. On the other hand, the IEEE 802.16e wireless metropolitan area network (WMAN) can offer wide coverage range and guarantee the quality of service requirement [4]. The hybrid WLAN and WMAN system can take advantages of them to offer high quality service. Therefore, the handoff in the hybrid IEEE 802.11 WLAN and IEEE 802.16e WMAN system becomes an important issue for the future wireless access networks.

In this thesis, we focus on a new "WLAN to WLAN/WiMax" handoff scenario which the mobile users mainly encounter in the hybrid WLAN and Mobile WiMax system as shown in Fig. 1.1. Because the WLAN has been widely deployed and the WiMax with wide coverage is dramatically developing in these years, one can imagine that the WiMax system will overlay on the existing WLAN in the near future. This new handoff scenario jointly considers the seamless issue in the horizontal and vertical handoff, i.e. "WLAN to WLAN" and "WLAN to WiMax", respectively [5]. Furthermore, the mobile station requires to select an appropriate network between WLAN and WiMax. Therefore, in addition to the seamless issue, the "always best

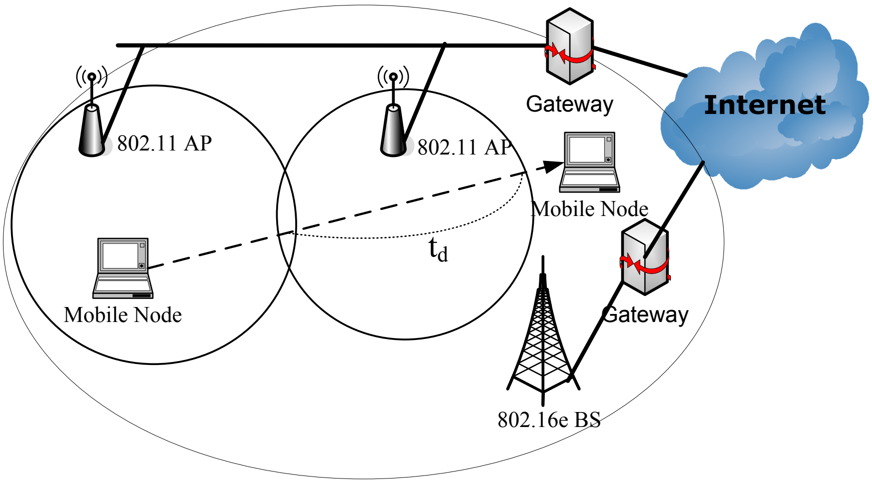


Figure 1.1: A new handoff scenario, "WLAN to WLAN/WiMax"

connect" (ABC) is also another important problem to deal with at the same time in this new handoff scenario.

The objectives of this thesis are two folds. First, we focus on minimizing the channel search latency for horizontal handoff in the WLAN, i.e. "WLAN to WLAN". Because the studies demonstrate that the channel search latency is the dominating factor for handoff latency in the WLANs and results in the large disconnection time. Therefore, we derive an analytical model to evaluate the channel search latency and its success probability. Based on this model, two new handoff performance metrics, namely "*single channel effective search time,* $t_{eff}^{(sc)}$" and "*multiple channel effective search time,* $t_{eff}^{(mc)}$", are defined as the ratio of the search latency to the success probability in one and multiple channels, respectively. By minimizing the $t_{eff}^{(sc)}$ or $t_{eff}^{(mc)}$, we obtain the optimum numbers of probe request/response transmissions during handoff to minimize the channel search latency.

Secondly, we develop a dynamic network selection scheme to determine the

Table 1.1: Link-layer handoff time for various WLAN cards [1]

	D-Link 520	Spectrum24	ZoomAir	Orinoco
Search	288ms	98ms	263ms	87ms
Execution	2ms	3ms	2ms	1ms
Total	290ms	101ms	265ms	88ms

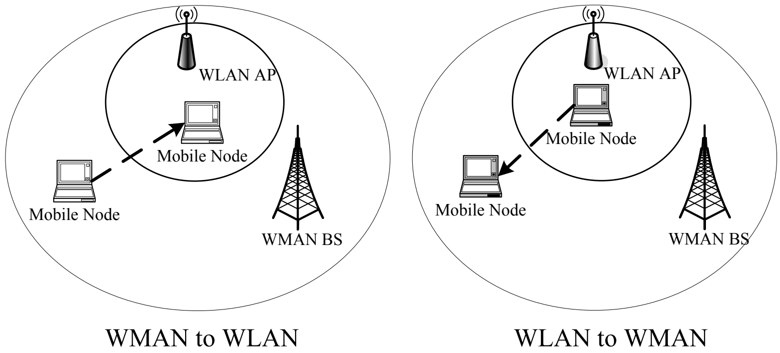
appropriate connecting system in the new "WLAN to WLAN/WiMax" handoff scenario which considers both the vertical and horizontal handoff. The proposed scheme requests the station awaiting an additional network selection time "t_w" before the selection to maximize the amount of delivered bits during a dwelling time. We formulate an optimization problem to find the maximum network selection time "$t_w^{(max)}$" for maximizing the delivered bits. In addition, we also find the saturation network selection time "$t_w^{(sat)}$" for optimizing the delivered bits and handoff latency during the dwelling time

1.1 Problem and Solution

1.1.1 Optimal Handoff Channel Search Time for Wireless Local Area Networks

In this part, the objective is to minimize the channel search latency for handoff in the IEEE 802.11 WLAN [2, 3]. In the literature, many studies measured the handoff latency in the IEEE 802.11 WLANs with the assumption that only one station exists [1, 6–8]. Under such a condition without collisions, their measurements indicated that the handoff latency ranges from 88 $\sim$ 290 msecs in the current IEEE 802.11 WLANs. More importantly, it was demonstrated that the search latency is the dominating factor for handoff latency as shown in Table 1.1.1 [1]. Thus, a number of new techniques were proposed to reduce the search latency in the IEEE 802.11 WLAN [1, 7, 9], but most of these results were obtained by simulations. In [1], the author proposed two constant timer, i.e. "maximum probe response timer" and "minimum probe response timer" to limit the channel search time. The author proposed selective probing to find APs in multiple channels in the WLAN in order to reduce the multiple channel search time, but the handoff station needs channel assignment information in the target network [9]. Some analytical models for evaluating the throughput and frame access delay of the IEEE 802.11 WLAN are available in the literature, but without considering handoff [10–15].

To our knowledge, an analytical approach to evaluate the impact of collisions on the search latency and success probability is still lacking in the literature. First, we propose an analytical approach to evaluate the channel search latency and its success probability in the IEEE 802.11 WLAN. The proposed analytical model considers the impacts of collisions resulted from the contentions of multiple stations. Secondly, two new handoff performance metrics, namely "*single channel effective search time*", $t_{eff}^{(sc)}$ and "*multiple channel effective search time*", $t_{eff}^{(mc)}$, are defined as the ratio of the search latency to the success probability in one and multiple channels, respectively. Basically, the $t_{eff}^{(sc)}$ and $t_{eff}^{(mc)}$ are the duration for which a station requires to successfully find an available AP during the handoff process in one and multiple channels, respectively. By minimizing the $t_{eff}^{(sc)}$ or $t_{eff}^{(mc)}$, we obtain the optimum numbers of probe request/response transmissions during handoff in terms of various constraints, such as low search latency or high successful search probability.



(a)

Figure 1.2: Two traditional vertical handoff scenarios, i.e. WMAN to WLAN and WLAN to WMAN

1.1.2 Network Selection with Joint Vertical and Horizontal Handoff in the Heterogeneous WLAN and Mobile WiMax System

In this part, the objective is to develop a network selection scheme in the "WLAN to WLAN/WiMax" handoff scenario with jointly considering vertical and horizontal handoff. In the literature, many studies have considered two conventional handoff scenarios, i.e. "WMAN to WLAN" and "WLAN to WMAN", as shown in Fig. 1.2(a). The objective in the first handoff scenario relates to the so called "always best connect" (ABC) [16]. Because a mobile user can concurrently connect to both the WLAN and WMAN, it requires to choose which system is the best for its service requirement. Some papers proposed cost function based vertical handoff decision algorithms to achieve the "ABC" objective in this handoff scenario [17,18]. However, to accurately obtain performance metrics anytime, such as available data rate, access latency and etc., is not easy for a mobile user in the first “WLAN to WMAN” handoff scenario with a mobile user in the overlapped region covered by both WLAN and WMAN. On the other hand, in the second “WLAN to WMAN” handoff scenario when a WLAN user enters a region covered only by WMAN, the “seamless” handoff issue is crucial because the mobile user needs fast transiting connections to the new WMAN in order to minimize the link disconnected time [19–21]. In [21, 22], the authors proposed the vertical handoff mechanisms which adopt fast Fourier transform for handoff detection and the dwelling timer concept to postpone the handoff decision in order to avoid unnecessary handoff and accurately make the decision.

However, since the WLAN has been widely deployed and the WiMax with wide coverage is dramatically developing in these years, one can imagine that the WiMax system will overlay on the existing WLAN in the near future. Thus, a new “WLAN to WLAN/WiMax” handoff scenario occurs as shown in Fig. 1.1. This new handoff scenario in the hybrid WLAN and WiMax system jointly considers the seamless issue in the horizontal and vertical handoff, i.e. “WLAN to WLAN” and “WLAN to WiMax”, respectively. Furthermore, the mobile station is requireed to select an appropriate network between WLAN and WiMax during handoff. Therefore, in addition to the seamless issue, the ABC is also another important problem to deal with at the same time in this new handoff scenario.

In this part, we develop a network selection scheme in the new “WLAN to WLAN/WiMax” handoff scenario to determine which system has the most delivered information bits during the dwelling time t_d. The proposed scheme requests the handoff station waiting for a short network selection time t_w before selecting the networks.

1.2 Thesis Outline

The rest of this thesis are organized as follows. Chapter 2 introduces the backgrounds on the IEEE 802.11 WLAN handoff process and IEEE 802.16e WMAN awakening process of sleep mode. In Chapter 3, we describe the analytical model for channel search latency and two new performance metrics, "*single channel effective search time*, $t_{eff}^{(sc)}$" and "*multiple channel effective search time*, $t_{eff}^{(mc)}$". In Chapter 4, we present a dynamic network selection scheme in the new "WLAN to WLAN/WiMax" handoff scenario. At last, Chapter 5 gives the concluding remarks and suggestions for future works.

CHAPTER 2

Background

In this chapter, we will give an overview on the IEEE 802.11 WLAN handoff process and IEEE 802.16e WMAN awakening process of sleep model [2, 4, 23].

2.1 IEEE 802.11 WLAN Handoff Process

The handoff procedure in IEEE 802.11 WLAN can be divided into two phases: search and execution phases, as shown in Fig. 2.1 [2, 23]. We described it apart as follows:

1. Search phase - In the beginning of the handoff procedure, the handoff station searches the available APs among all the channels, e.g. 11 channels in USA. In this phase, two methods are suggested in the standard: the passive and active scanning modes. In the passive scanning mode, the handoff station periodically listens to the beacon frames generated by APs. Thus, if the beacon period is 100 msecs, a handoff station in passive scanning mode has to wait 1.1 secs to search all the channels. On the other hand, instead of passively listening to the beacon, the handoff station in the active scanning mode broadcasts a probe request frame and waits for the responses from APs, as shown in Fig. 2.1. Since the contentions among stations influence the success of the handshaking procedure, the search latency in the active scanning mode may not be a deterministic value. Thus, it is interesting to investigate the search latency and success probability in the active

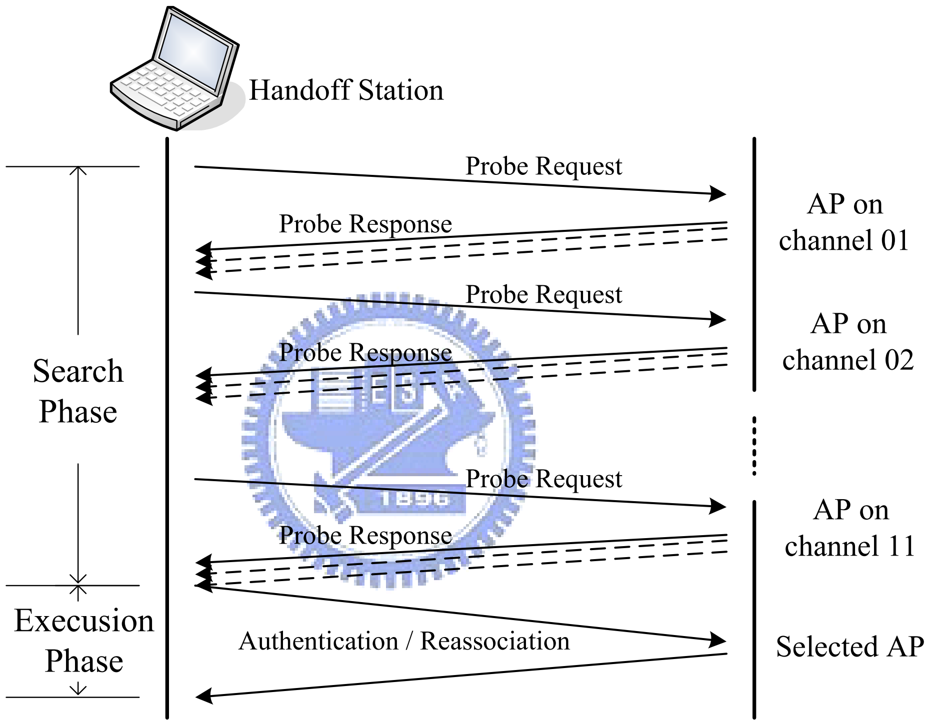


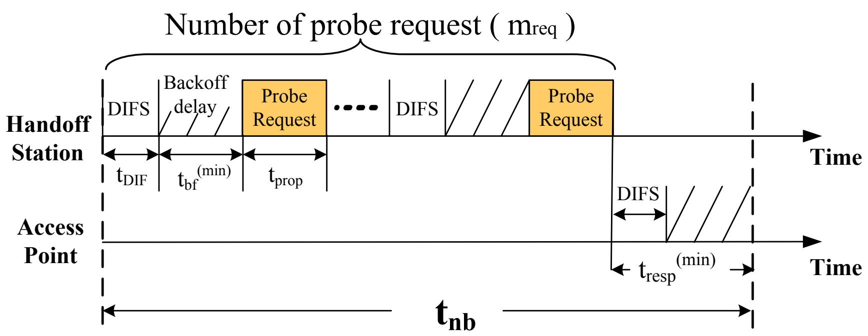
Figure 2.1: The handoff procedure with active scanning in the IEEE 802.11 WLANs

scanning mode, which will be the focus of this paper.

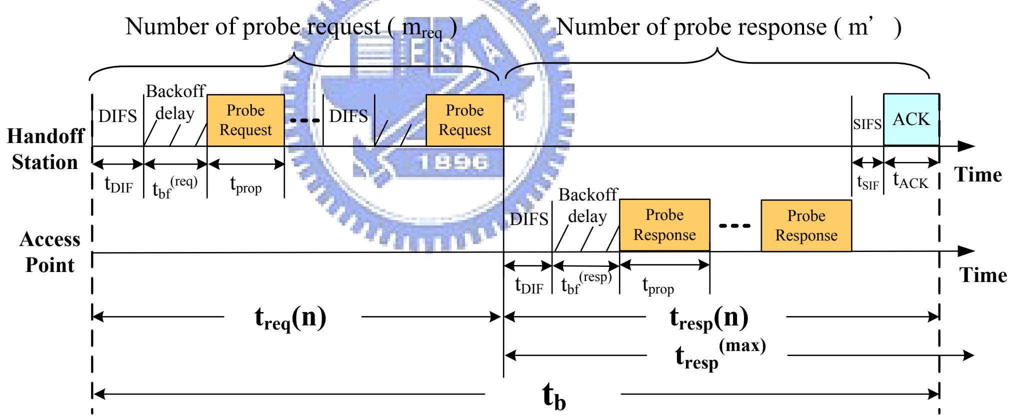
2. Execution phase - After searching the available APs in the channels, the handoff station selects one of the APs to connect. The station sends the authentication and reassociation request to the target AP to get the permission for joining the network. If the target AP permits, it replies the authentication and reassociation response to the station; Otherwise, it just rejects the request. As shown in Table 1.1.1, the latency in the execution phase is only 2 msecs and can be neglected compared to that in the search phase [1, 6, 7]. Therefore, it is more important to study the latency and success probability in the search phase than that in the execution phase.

2.1.1 Procedures in the active scanning mode

In the active scanning mode, the handoff station broadcasts the probe request frame by m_{req} times to search the APs at each channel following the carrier-sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol, as shown in Fig. 2.2. And then, it waits for the probe response frame from APs. If the channel is idle for a minimum probe response time $t_{resp}^{(min)}$, the handoff station change to the next channel and repeats the handshaking, as shown in Fig. 2.2(a). This channel is defined as the "*idle channel*" where no APs or stations use this channel. On the contrary, if the channel is no idle, the station waits for the probe response frame from other APs until reaching the maximum probe response time $t_{resp}^{(max)}$. To ensure a station successfully receiving the frame, the APs retransmit m' probe response frames until it successfully receives the ACK frame from the station. The detailed procedures and the timing diagram of active scanning in an used channel are shown in Fig. 2.2(b). To ease the notation, we denote this channel as the "*busy channel*".



(a)



(b)

Figure 2.2: The handshaking of active scanning mode in an (a) idle and (b) busy channel.

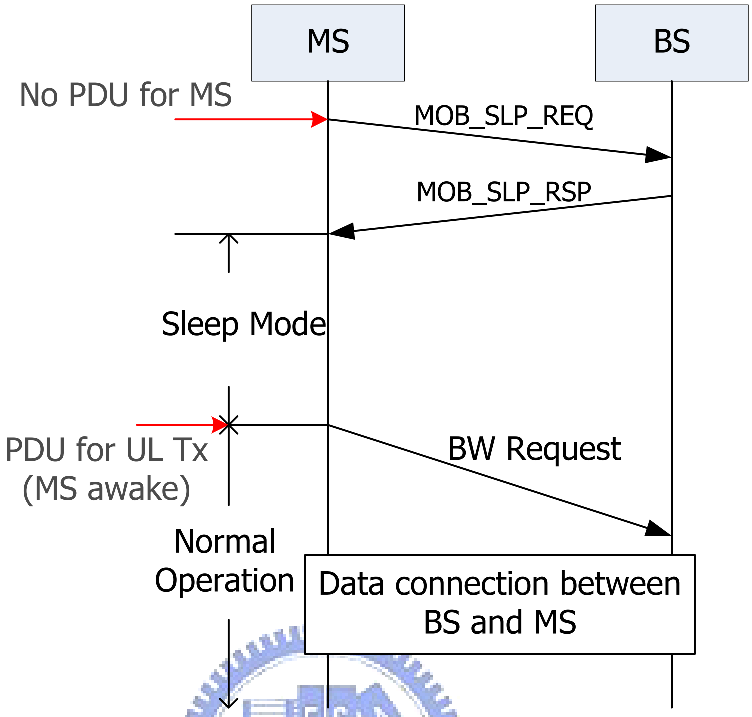


Figure 2.3: Signaling of sleep mode transition by station initiation in the IEEE 802.16e

2.2 The Awakening Process in the IEEE 802.16e

In the hybrid WLAN and WMAN system, the coverage area of several WLANs can be overlapped by the coverage of a WMAN, as shown in Fig. 1.1. Consider a mobile station with dual interfaces consisting of IEEE 802.11 and IEEE 802.16e. It is assumed that this mobile stations stays in the WMAN so that the network re-entry process is unnecessary [24]. When the station switches the connection to WLAN, the WiMax interface can change to the sleep mode based on the handshaking procedure shown in Fig. 2.3. To restore the data connection, the WiMax interface follows the random access procedures defined in the standard and merely sends the bandwidth request frame [4, 25, 26]. Therefore, in this paper, we consider the influence of the awakening process in the "WLAN to WiMax" handoff scenario.

CHAPTER 3

Optimal Handoff Channel Search Time for Wireless Local Area Networks

In this chapter, we derive an analytical model to calculate the single and multiple channel search latency and its success probability for handoff in the IEEE 802.11 WLAN. In addition, based on this model, we define two new performance metrics, $t_{eff}^{(sc)}$ and $t_{eff}^{(mc)}$, as the ratio of the search latency to the success probability in one and multiple channels, respectively. By minimizing these two metrics, we obtain the optimum numbers of probe request/respone transmissions as the handoff occurs. Finally, we present an algorithm for performing the optimal channel search in terms of various constrains, such as low search latency or high successful search probability.

The rest of this chapter are organized as follows. Section 3.1 analyzes the search latency during handoff. In Section 3.2, we discuss the performance metrics $t_{eff}^{(sc)}$ and $t_{eff}^{(mc)}$. Section 3.3 shows the numerical results. The concluding remarks are given in Section 3.4.

3.1 Analysis

In this section, we develop an analytical model for evaluating the search latency in the IEEE 802.11 active scanning mode as shown in Fig. 2.2. The latency in searching single channel includes two possible scenarios: (1) the search latency in an busy channel t_b; (2) the search latency in an idle channel t_{nb}.

3.1.1 Search latency in the busy channel

In Fig. 2.2(b), the search latency in the busy channel consists of two parts: (1) the time in broadcasting all the probe request frames t_{req}, and (2) the latency for which the target AP successfully replies the probe response frame t_{resp}. The difference between the transmissions of the probe request and response is that the AP has to successfully receive the ACK frames in the later case; whereas the handoff station does not in the former case. In addition, we further consider the impact of the number of existing stations n in the target network. The average search latency in the busy channel t_b can be expressed as

$$t_b(n) = t_{req}(n) + t_{resp}(n) \ ; \tag{3.1}$$

whereas the maximum search latency in the busy channel $t_b^{(max)}$ can be given by

$$t_b^{(max)}(n) = t_{req}^{(max)}(n) + t_{resp}(n) \ . \tag{3.2}$$

The abbreviations of the notations for the following analysis are shown in Table 3.1.

(1) Average time in broadcasting probe request, t_{req}

Consider the situation that the AP may successfully receive the probe request frame and reply the response frame before the handoff station consecutively broadcasting m_{req} probe request frames. Then, the average latency for broadcasting m_{req} probe request frames can be given by

$$\begin{aligned} t_{req}(n) &= (1-p)T + p(1-p)2T + p^2(1-p)3T + ... \\ &\quad + p^{m_{req}-1}(1-p)(m_{req}-1)\cdot T + p^{m_{req}} m_{req}\cdot T \\ &= T\cdot(\frac{1-p^{m_{req}}}{1-p}) \ , \end{aligned} \tag{3.3}$$

Table 3.1: Abbreviations of terminology used in the analytical model

t_{DIFS}	Duration of DIFS
t_{SIFS}	Duration of SIFS
t_{ACK}	Duration of ACK
t_{prop}	Transmission and propagation delay for sending probe request or response
W	Minimum backoff window size
σ	Duration of an empty slot

where p is the failure probability in broadcasting the probe request frame which will be described the detail later; and T is the duration for broadcasting one probe request frame. Thus as shown in the Fig. 2.2(b), T can be written as

$$T = (t_{DIFS} + t_{bf}^{(req)}(n) + t_{prop}) \ , \tag{3.4}$$

where $t_{bf}^{(req)}(n)$ is the average backoff time of a handoff station before sending a probe request frame. Given the average number of backoff slots $E[W_{req}]$ for the probe request frame and the average waiting time of a backoff slot $E[T_{wait}]$, we can express $t_{bf}^{(req)}(n)$ as

$$t_{bf}^{(req)}(n) = E[W_{req}] \cdot E[T_{wait}] \ . \tag{3.5}$$

Since the backoff window size of every probe request transmission is W, the average number of backoff slot is then

$$E[W_{req}] = \frac{W-1}{2} \ . \tag{3.6}$$

In addition, according to the developed analytical model in [11, 15], the average waiting time of a backoff slot $E[T_{wait}]$ is

$$E[T_{wait}] = (1-P_s) \cdot P_{tr} \cdot T_c + P_s \cdot P_{tr} \cdot T_s + (1-P_{tr}) \cdot \sigma \ , \tag{3.7}$$

where T_s and T_c are the average time that the medium is busy due to a successful transmission or a collision, respectively; P_s is the success probability of a frame transmission; and P_{tr} is the probability that at least one frame is transmitted. Since the contentions against the existing stations in the target networks occur, the probabilities P_s and P_{tr} become

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} , \tag{3.8}$$

$$P_{tr} = 1 - (1-\tau)^n , \tag{3.9}$$

where τ is the probability that a station transmits a frame. Consider a contention window with a size ranged from W and $2^m W$, and the maximum number of retransmissions of the existing stations in the target network is $m + f$. Then, following the steps in [10, 14], we can obtain

$$p = 1 - (1-\tau)^{n-1} , \tag{3.10}$$

$$\tau = \frac{2(1-2p)(1-p^{m+f+1})}{(1-2p)(1-p^{m+f+1}) + W[1-p-p(2p)^m(1+p^f-2p^{f+1})]} , \tag{3.11}$$

Equations (3.10) and (3.11) can be solved recursively for given n, f, m and W. Therefore, the latency in broadcasting probe request frame, $t_{req}(n)$ can be obtained by substituting (3.5)∼(3.11) into (4.7).

Next, consider the case that the AP replies the probe response frame to the handoff station only after receiving the last probe request frame. Thus, the maximum time in broadcasting probe request frame $t_{req}^{(max)}$ can be written as

$$t_{req}^{(max)}(n) = T \cdot m_{req} , \tag{3.12}$$

where T can be obtained by (3.4).

(2) Latency of replying probe response, t_{resp}

Denote $t_{bf}^{(resp)}(n)$ as the average latency that the target AP successfully sends the probe response to the handoff station. Then , as shown in Fig. 2.2(b), the average latency that the target AP successfully replies probe response frames $t_{resp}(n)$, can be written by

$$t_{resp}(n) = t_{DIFS} + t_{bf}^{(resp)}(n) + t_{prop} + t_{SIFS} + t_{ACK} \ . \tag{3.13}$$

Similar to (3.5) and given the average number of backoff slots in replying the probe response frames $E[W_{resp}]$, we can express $t_{bf}^{(resp)}(n)$ as

$$t_{bf}^{(resp)}(n) = E[W_{resp}] \cdot E[T_{wait}] \ . \tag{3.14}$$

Different from $E[W_{req}]$, since the target AP has to wait for the ACK frame from the handoff station and then retransmits the probe response by m' times, $E[W_{resp}]$ is given by

$$\begin{aligned} E[W_{resp}] &= (1-p)\frac{W+1}{2} + p(1-p)(\frac{W+1}{2} + \frac{2W+1}{2}) + \ldots \\ &+ p^{m'}(1-p)(\frac{W+1}{2} + \frac{2W+1}{2} + \ldots + \frac{2^{m'} \cdot W+1}{2}) \\ &+ p^{m'+1}(\frac{W+1}{2} + \frac{2W+1}{2} + \ldots + \frac{2^{m'} \cdot W+1}{2}) \\ &= \frac{W}{2} \cdot \frac{1-(2p)^{m'+1}}{1-2p} \ + \ \frac{1}{2} \cdot \frac{1-p^{m'+1}}{1-p} \ . \end{aligned} \tag{3.15}$$

Substituting (3.7∼3.11) and (3.14∼3.15) into (3.13), we can obtain $t_{resp}(n)$.

3.1.2 Search latency in the idle channel

The search latency in an idle channel t_{nb} is the time that the handoff station has to stay in the idle channel before it switches to the next channel. As shown in Fig. 2.2

(a), the search latency t_{nb} is given by

$$t_{nb} = (t_{DIF} + t_{bf}^{(min)} + t_{prop}) \cdot m_{req} + t_{resp}^{(min)} \ , \tag{3.16}$$

where $t_{bf}^{(min)}$ is the average backoff time before transmitting a probe request frame in an idle channel. Different from (3.5), the handoff station does not have to contend with other stations since the channel is idle. Therefore, $t_{bf}^{(min)}$ can be written as

$$t_{bf}^{(min)} = \frac{(W-1)}{2} \cdot \sigma \ . \tag{3.17}$$

Furthermore, in (3.16), the minimum probe response time $t_{resp}^{(min)}$ is the time that the handoff station has to stay in the idle channel. Considering the longest backoff time a frame transmission, the minimum probe response time $t_{resp}^{(min)}$ can be given by

$$t_{resp}^{(min)} \geq t_{DIFS} + (W-1) \cdot \sigma \ . \tag{3.18}$$

3.2 New Performance Metrics

Intuitively, as the numbers of transmissions of the probe request m_{req} and the probe response m' increase, the successful search probability in an *busy* channel $P_s^{(sc)}$ also increases. However, the handoff latency also increases as the number of transmissions increases. To take this phenomenon into account in determining m_{req} and m', we define two new performance metrics, called "*single channel effective search time* , $t_{eff}^{(sc)}$" and "*multiple channel effective search time* , $t_{eff}^{(mc)}$".

3.2.1 Single Channel Effective Search Time

The single channel effective search time $t_{eff}^{(sc)}$ is defined as the ratio of the search latency t_b to the successful search probability $P_s^{(sc)}$. It can be considered as the time for which a handoff station requires to successfully search an available AP in an busy channel. Thus, we have

$$t_{eff}^{(sc)} = \frac{t_b(n, m', m_{req})}{P_s^{(sc)}(n, m', m_{req})} \ . \tag{3.19}$$

In addition, considering the maximum search latency $t_b^{(max)}$, we have the maximum single channel effective search time

$$t_{eff\_max}^{(sc)} = \frac{t_b^{(max)}(n, m', m_{req})}{P_s^{(sc)}(n, m', m_{req})} \ . \tag{3.20}$$

Since the search process is successful only when both the probe request and response frames are successfully received, thus it is followed that

$$P_s^{(sc)}(n, m', m_{req}) = P_s^{(req)}(n, m_{req}) \cdot P_s^{(resp)}(n, m') \ , \tag{3.21}$$

where $P_s^{(req)}(n, m_{req}) = 1 - [1 - (1 - \tau)^n]^{m_{req}}$ and $P_s^{(resp)}(n, m') = 1 - p^{m'+1}$ are the successful probabilities in broadcasting the probe request frame and replying the probe response frame, respectively. Through $t_{eff}^{(sc)}$, We can obtain the optimum values of m_{req} and m' for the minimum successful search latency.

3.2.2 Multiple Channel Effective Search Time

Similarly, the multiple channel effective search time $t_{eff}^{(mc)}$ is the time that a handoff station successfully searches an AP while scanning whole the channels, including used and idle ones. Thus, the $t_{eff}^{(mc)}$ can be written as

$$t_{eff}^{(mc)} = \frac{t^{(mc)}(n, m', m_{req}, x)}{P_s^{(mc)}(n, m', m_{req}, x)} \ , \tag{3.22}$$

where $t^{(mc)}$ and $P_s^{(mc)}$ are the time and probability that the handoff station can successfully search at least one AP among the x channels, respectively. Since the channel condition and the probability of AP existing in each channel P_i are different. Therefore, $t^{(mc)}$ and $P_s^{(mc)}$ can be written as

$$t^{(mc)} = \sum_{i=1}^{x}(P_i \cdot t_{b,\ i} + (1 - P_i) \cdot t_{nb}) \ , \tag{3.23}$$

$$P_s^{(mc)} = 1 - \prod_{i=1}^{x}(1 - P_{s,\ i}^{(sc)} \cdot P_i) \ , \tag{3.24}$$

where $t_{b,\ i}$ and $P_{s,\ i}^{(sc)}$ are the channel search time and successful search probability in the busy channel i, respectively.

3.3 Numerical Results

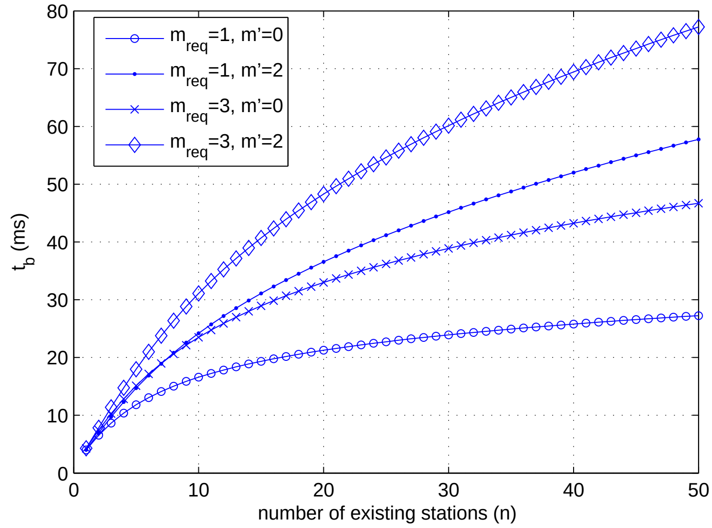
In this section, we show the numerical results regarding the search latency t_b and success probability $P_s^{(sc)}$ with different number of stations n, probe request m_{req} and probe response transmission m'. Through *single channel effective search time* $t_{eff}^{(sc)}$ and *multiple channel effective search time* $t_{eff}^{(mc)}$, we can find the optimum values of m_{req} and m' to minimize the successful search latency in one and multiple channels, respectively. The related system parameters are shown in Table 4.2.

3.3.1 Search Latency and Successful Search Probability

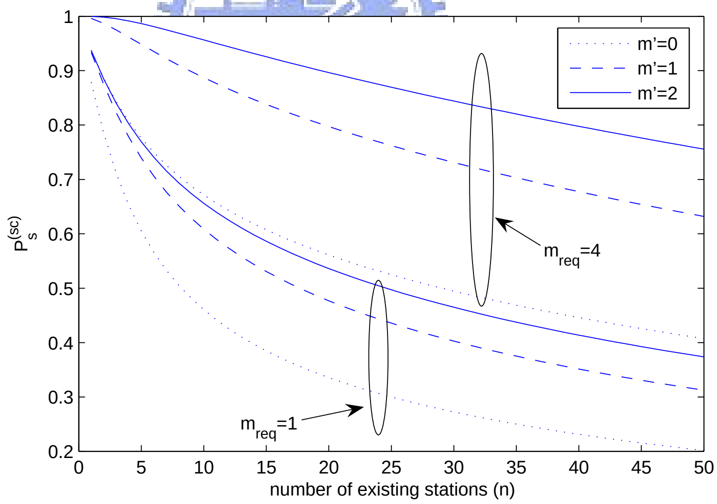
Figure 3.1(a) shows the average search latency t_b versus the number of stations n with various values of m_{req} and m'. As shown in the figure, the average search latency t_b increases as the number of stations increases due to collisions. However, when the number of stations is large, t_b increases slowly because more collisions result in reaching the maximum number of the probe request/response transmissions. Both the handoff station and AP give up the transmissions in this channel. Thus, we can expect that the success probability $P_s^{(sc)}$ becomes smaller with more stations, as

Table 3.2: System parameter Values

Data frame bit rate	11 Mbps
Management frame bit rate	1 Mbps
Packet payload	1500 bytes
MAC/PHY header	222/128 bits
ACK	112 bits
Slot time, σ	20 μsec
SIFS/DIFS	10/50 μsec
Minimum/Maximum CW	32/1024
Retry limit,$m + f$	7



(a)



(b)

Figure 3.1: Impacts of numbers of the existing stations n on the (a)average search latency t_b and (b)success probability $P_s^{(sc)}$ with various m_{req} and m'.

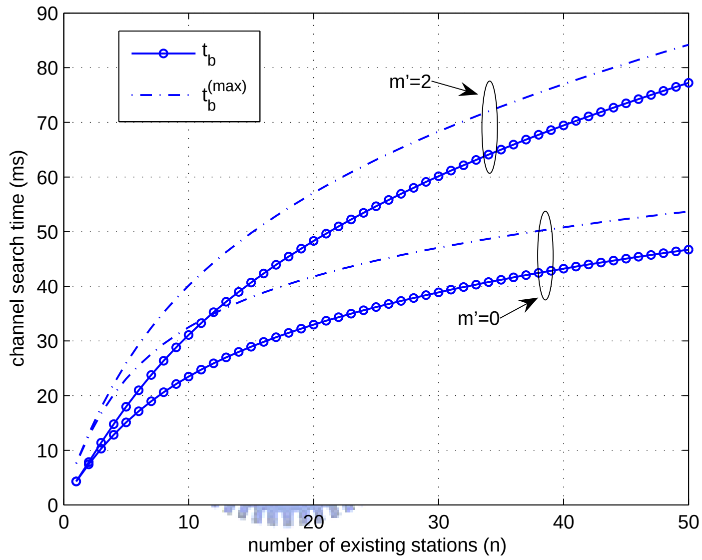


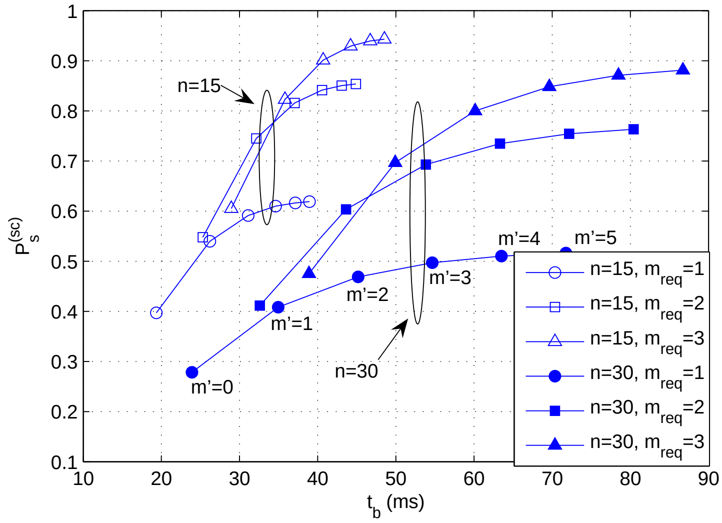
Figure 3.2: Comparison between the average search time t_b and maximum search time $t_b^{(max)}$ with m_{req}=3.

shown in Fig. 3.1(b). In addition, We also show the comparison between t_b and $t_b^{(max)}$ in the Fig. 3.2. We can find out that there is a nearly constant gap (10%) between t_b and the maximum search latency $t_b^{(max)}$ with various m_{req} and m'. Therefore, the upper bond of search time in a busy channel is about 10% larger than average search time.

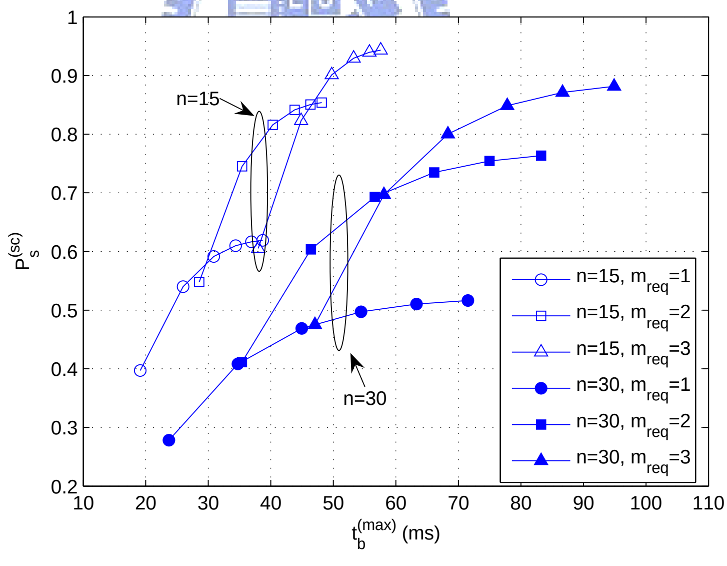
Furthermore, in Fig. 3.1(b), $P_s^{(sc)}$ increases as m_{req} or m' increases due to the large numbers of the probe request or response frame transmissions. However, the increase on $P_s^{(sc)}$ by m' is less efficient than that by m_{req} due to the low success probability in broadcasting probe request $P_s^{(req)}$. Therefore, the handoff station has to appropriately adjust both m_{req} and m' to achieve high successful search probability $P_s^{(sc)}$, instead only one of them.

3.3.2 Search Latency vs Successful Search Probability

Figure 3.3 shows the impacts of the average search latency t_b and maximum search latency $t_b^{(max)}$ on the successful search probability $P_s^{(sc)}$ for the number of stations $n =$ 15 and 30. The values of m_{req} and m' can be chosen for various system requirements, such as high success probability or low search latency. For instance, Assume that the requirement is $P_s^{(sc)} \geq 0.8$ at $n = 15$. (1) In the maximum search latency $t_b^{(max)}$ case as shown in Fig. 3.3(b), the combination of $m_{req} = 2$ and $m' = 2$ is preferred to the combination of $m_{req} = 3$ and $m' = 1$ due to the low search latency. (2) In the average search latency t_b case as shown in Fig. 3.3(a), the combination of m_{req} and m' is contrary to maximum search latency case due to low search latency. Furthermore, Assume that the constraint is $t_b \leq 50$ msecs at $n = 30$. In the maximum search latency case, $m_{req} = 2$ and $m' = 1$ is adopted because of the high successful search probability.



(a)



(b)

Figure 3.3: Impact of (a) average search latency t_b and (b) maximum search latency $t_b^{(max)}$ on successful search probability $P_s^{(sc)}$

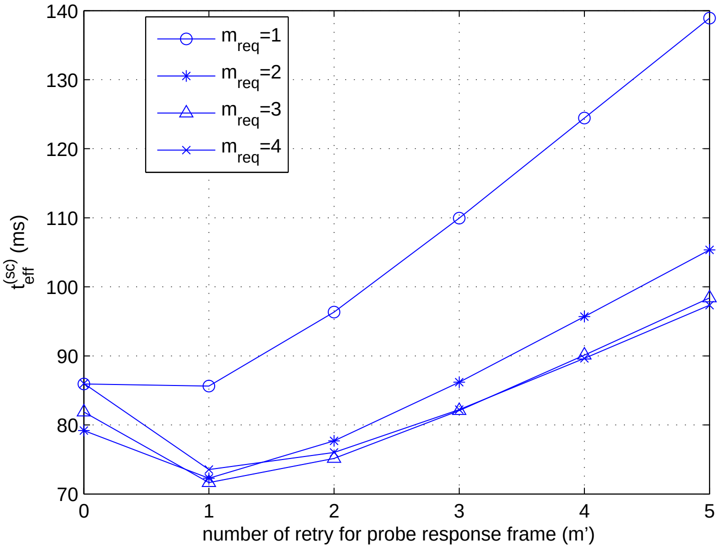
3.3.3 Performance on Single Channel Effective Search Time

Figure 3.4 shows the *single channel effective search time* $t_{eff}^{(sc)}$ and maximum *single channel effective search time* $t_{eff\_max}^{(sc)}$ for various numbers of probe request/response transmissions with the number of stations $n = 30$, respectively. As shown in Fig. 3.1(a), the $t_{eff}^{(sc)}$ may not become shorter for smaller m_{req} and m' due to the small success probability $P_s^{(sc)}$. Therefore, an optimum choice for the m_{req} and m' values exists in the sense of minimizing the $t_{eff}^{(sc)}$. For example, in the Fig. 3.4(a), the lowest $t_{eff}^{(sc)}$ occurs at $m_{req} = 3$ and $m' = 1$. However, in the maximum case of $t_{eff}^{(sc)}$ as shown in the Fig. 3.4(b), the lowest $t_{eff\_max}^{(sc)}$ occurs at $m_{req} = 2$ and $m' = 1$.

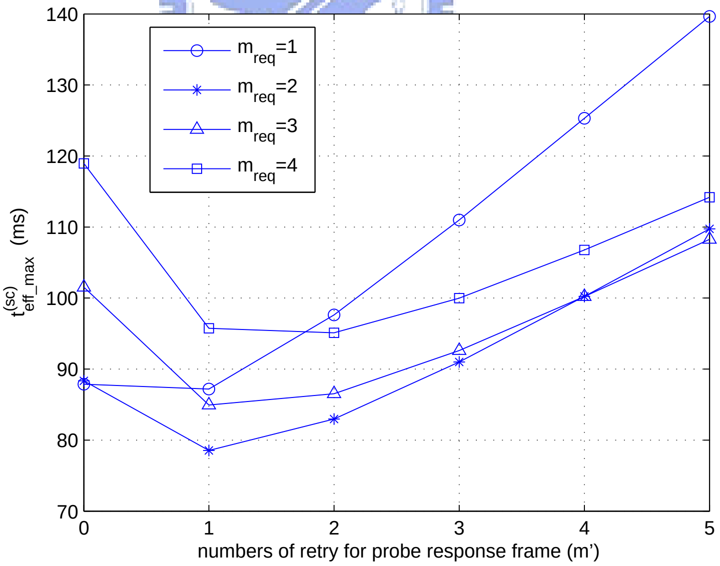
Figure 3.5 shows the $t_{eff}^{(sc)}$ versus the number of existing stations for three different system requirements. As shown in the figure, the value of $t_{eff}^{(sc)}$ in the minimum $t_{eff}^{(sc)}$ case can be reduced by 30% compared to the legacy case with $m_{req} = 1$ and $m' = 0$. For the requirements of the minimum $t_{eff}^{(sc)}$, both the values of m_{req} and m' is obtained by choosing the set with the lowest $t_{eff}^{(sc)}$. As for the minimum search latency t_b, i.e. $(m_{req}, m') = (1, 0)$, the $t_{eff}^{(sc)}$ is slightly higher than that in the system with the minimum $t_{eff}^{(sc)}$. Because in the former system the successful search probability is low, the $t_{eff}^{(sc)}$ increases due to the retransmissions. At last, for the requirements is $P_s^{(sc)} \geq 0.8$, the $t_{eff}^{(sc)}$ is the highest among the other systems. To ensure the high success probability, the large number of retransmissions leads to longer search latency and $t_{eff}^{(sc)}$.

3.3.4 Multiple Channel Effective Search Time

Figure 3.6 shows the latency that the handoff station can successfully search at least one available AP from whole the channels, i.e. number of channels $x = 11$, using active scanning. Assume that any two channels in the x channels are i.i.d (independent identically distributed) and there are α busy channels among the x channels. Thus,



(a)



(b)

Figure 3.4: (a) $t_{eff}^{(sc)}$ and (b) $t_{eff\_max}^{(sc)}$ versus m' and m_{req} for number of station $n = 30$.

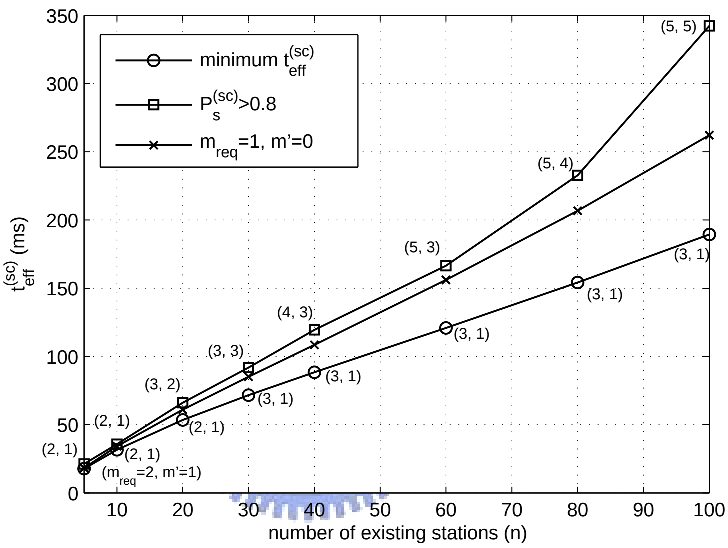


Figure 3.5: Impacts of different system requirements on $t_{eff}^{(sc)}$, where (x, y) represent the numbers of probe requests (m_{req}) and probe responses (m')

the probability of AP existing in each channel P_i in the equations (4.10∼4.8) can be equaled to $P = \frac{\alpha}{x}$. As shown in the figure, for 100 contending stations and one busy channel, the value of $t_{eff}^{(mc)}$ in the optimum case can be reduced by 40% compared to the case with m_{req}=1 and m'=0. This is because the case with m_{req}=1 and m'=0 has low successful search probability, and the low successful search probability leads the handoff station to repeat scanning the whole channels, including the used and idle channels. In addition, as the number of busy channel $\alpha > 5$, the $t_{eff}^{(mc)}$ in both cases approach the same due to the successful search probability approach to unity as α increases. This result indicates that when the handoff station locates in a crowed region where the most channels are used, the handoff station only needs to minimize values of m_{req} and m', i.e. m_{req}=1 and m'=0. However, when the handoff station locates in a sparse region where few channels are used, the handoff station needs to properly adjust m_{req} and m' to achieve minimum successful search latency.

3.4 Conclusions

In this chapter, we develop an analytical model to compute the search latency and successful search probability in the IEEE 802.11 WLANs active scanning mode. The proposed model considers two kinds of frame transmissions: (1) the broadcasts of the probe request frame from the handoff station, and (2) the replies of the probe response frame from the target AP. In addition, the analytical model also considers the impacts of collisions due to the contentions against the existing stations in the target network.

From the developed model, we can analytically evaluate the search latency and success probability for the handoff in IEEE 802.11 WLAN. Moreover, we define two new handoff performance metrics, named "*single channel effective search time* , $t_{eff}^{(sc)}$" and "*multiple channel effective search time* , $t_{eff}^{(mc)}$", which can be used to find

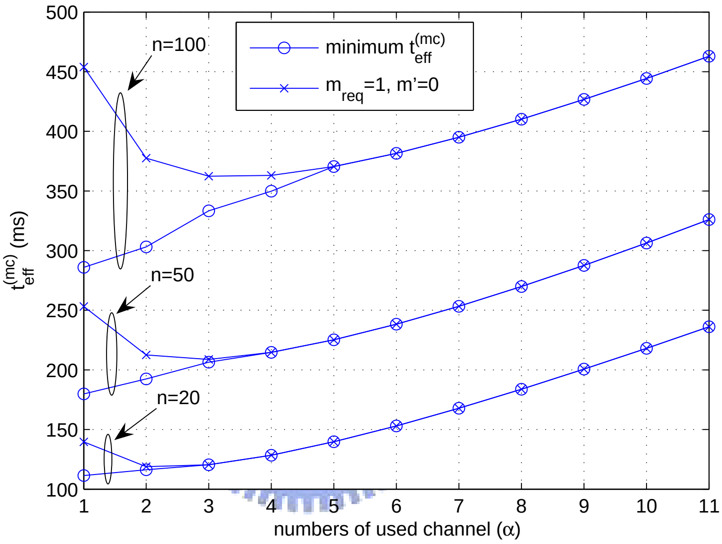


Figure 3.6: Impacts of different system requirements on $t_{eff}^{(mc)}$ with number of station n and number of channel $x = 11$

the optimal handoff parameters in one *busy* channel and multiple busy/idle channels, respectively. The numerical results show that the system with small number of probe request/response frame transmission may not have lowest $t_{eff}^{(sc)}$ or $t_{eff}^{(mc)}$. Therefore, the handoff station has to adjust accordingly the handoff parameters, i.e. m_{req} and m', to minimize the $t_{eff}^{(sc)}$ or $t_{eff}^{(mc)}$.

CHAPTER 4

Network Selection with Joint Vertical and Horizontal Handoff in the Heterogeneous WLAN and Mobile WiMax System

In this chapter, we develop a dynamic network selection scheme to determine the connecting system in a new "WLAN to WLAN/WiMax" handoff scenario which considers both the vertical and horizontal handoffs. The proposed scheme requests the station awaiting an additional network selection time "t_w" before the selection to maximize the amount of delivered bits during a dwelling time. We formulate an optimization problem to find the maximum network selection time "$t_w^{(max)}$" for maximizing the delivered bits. In addition, we also find the saturation network selection time "$t_w^{(sat)}$" for optimizing the delivered bits and handoff latency during the dwelling time and show that the proposed scheme can improve the delivered information bits during handoff.

The rest of this chapter are organized as follows. Section 4.1 introduces the system overview on the proposed network selection scheme. Section 4.2 formulates the problem and analyzes the delivered information bits during the dwelling time. Section 4.3 shows the numerical results. The concluding remarks are given in the section 4.4.

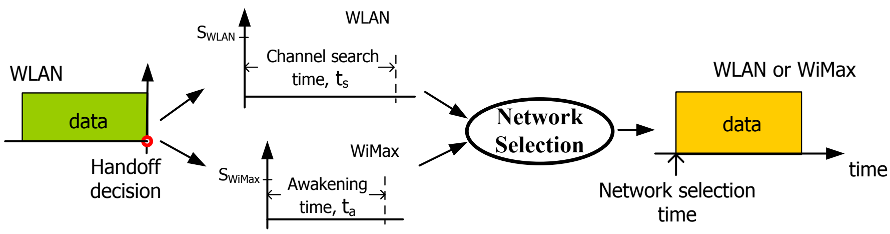


Figure 4.1: System model for jointly vertical and horizontal handoff in considered handoff "WLAN to WLAN/WiMax" scenario

4.1 System Overview

In this section, we describe the considered system model and the proposed network selection scheme for the new "WLAN to WLAN/WiMax" handoff scenario. At last, we formulate the optimization problems to find the two network selection times, i.e. $t_w^{(max)}$ and $t_w^{(sat)}$.

4.1.1 System Model

Figure 1.1 illustrates a new "WLAN to WLAN/WiMax" handoff scenario considered in this paper. Let a dual-interface mobile station switch to WLAN for transmitting data, while preserving a connection in the IEEE 802.16e sleep mode [4, 27]. As the station moves and the signal strength received from the serving AP is below a predefined threshold, the channel search and awakening processes in WLAN and WiMax will be respectively executed, as shown in Fig. 4.1. At last, the station performs the network selection procedure to determine the appropriate system that has the maximum delivered information bits during the dwelling time t_d.

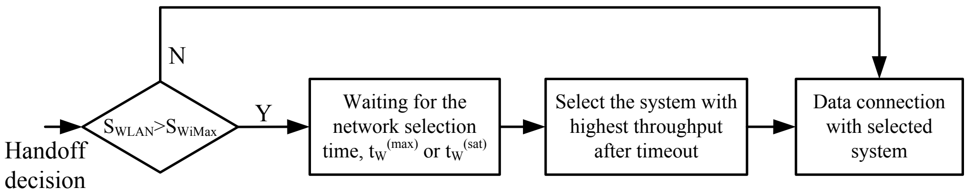


Figure 4.2: Proposed network selection scheme in WLAN to WLAN/WiMax

4.1.2 Proposed Network Selection Scheme

The proposed network selection scheme between WLAN and WiMax is depicted in Fig. 4.2. Assume that the WiMax system successfully establishes the connection first. Then, if the per user throughput in WiMax is higher than that in WLAN, the station creates the data connection with WiMax immediately. Otherwise, the mobile station waits for the maximum network selection time $t_w^{(max)}$ or saturation network selection time $t_w^{(sat)}$ before selecting the system with the highest per user throughput. At last, the station creates the data connection with selected system.

4.2 Performance Analysis

In this section, we formulate the optimization problems to find the two network selection times, i.e. $t_w^{(max)}$ and $t_w^{(sat)}$. Then, we analyze the impact of network selection time t_w on the delivered information bits during the dwelling time t_d in the new "WLAN to WLAN/WiMax" handoff scenario.

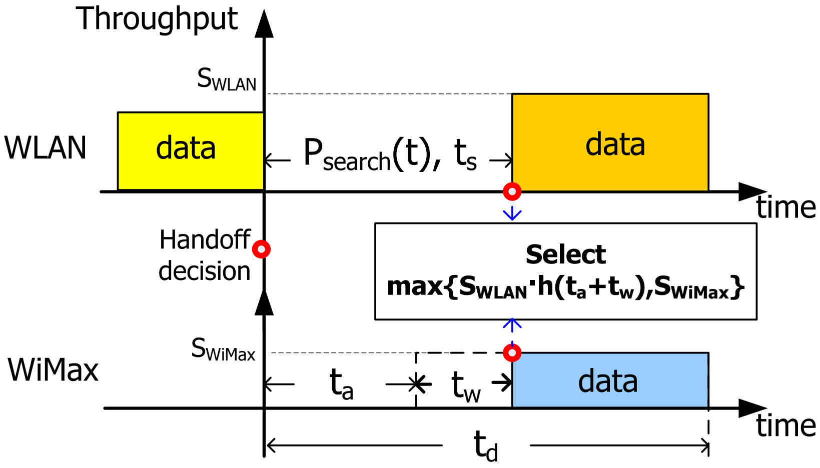


Figure 4.3: Time diagram of network selection between IEEE 802.16e and IEEE 802.11

Table 4.1: A example for performance in WLAN to WLAN/WiMax

	number of stations in target network	MAC throughput per user (Mbps)	handoff latency (ms)
WLAN to WLAN (horizontal)	10 (user density: 0.3 users/m^2)	4.35 (S_{WLAN})	30 (t_s)
WLAN to WiMax (vertical)	50 (user density: 0.008 users/m^2)	1.01 (S_{WiMax})	10 (t_a)

Note: The coverage range of WLAN and WiMax is 100 and 1400 meters, respectively.

4.2.1 Problem Formulation

Because both WLAN and WMAN use distinct access techniques, the channel search time t_s in WLAN differs from the awakening time t_a in WiMax. In addition, the available per user throughput in WLAN and WiMax, denoted as S_{WLAN} and S_{WiMax}, respectively, are also different due to different coverage. Therefore, we can expect that a handoff station can deliver more information bits if it can postpone the network selection for a short duration after one of the interfaces successfully establishing a new connect. From Table 4.1, we find that WiMax has short awakening latency, i.e. $t_a = 10ms$, but has lower available per user throughput than that in WLAN. The problem is how long the handoff station has to wait before selecting the networks so that it can maximize the delivered bits during the dwelling time.

Figure 4.3 illustrates the timing diagram of the network selection in the hybrid WLAN and WiMax system. After waiting a network selection time t_w, the handoff station selects the system i with the highest available throughput according to

$$i = \begin{cases} \text{WLAN}, & \text{if } S_{\text{WLAN}}(n_{11}) \cdot h(t_a + t_w) \geq S_{\text{WiMax}}(n_{16}) \\ \text{WiMax}, & \text{otherwise} \end{cases}, \tag{4.1}$$

where n_{11} and n_{16} are the number of stations in the target WLAN and WMAN, respectively. The function $h(t_a + t_w)$ indicate the event that channel search process in WLAN is successful after a duration of $t_a + t_w$, i.e.

$$h(t_a + t_w) = \begin{cases} 1\ , & \text{if WLAN channel search succeed} \\ & \text{after } t_a + t_w \\ 0\ , & \text{otherwise} \end{cases}. \tag{4.2}$$

However, the dwelling time (t_d) in the target network is limited, and the station may not always succeed in the channel search process of WLAN. Thus, the previous problem can be formulated to find the maximum network selection time "$t_w^{(max)}$" under the delay constraint d_i such that the delivered bits during the dwelling time t_d can be maximized, i.e.,

$$\begin{aligned} t_w^{(max)} = \arg\max_{0 \leqslant t_w \leqslant d_i - t_a} \{ & [P_{search}(t_w + t_a) \cdot S_{\text{WLAN}}(n_{11}) \\ & + (1 - P_{search}(t_w + t_a)) \cdot S_{\text{WiMax}}(n_{16})] \\ & \cdot (t_d - t_w - t_a)\} \ , \end{aligned} \tag{4.3}$$

where $P_{search}(t_a+t_w)$ is the success probability during the channel search time t_a+t_w in WLAN. Furthermore, we also find the saturation network selection time "$t_w^{(sat)}$" during the dwelling time t_d because the delivered bits improvement is small as the network selection time t_w exceeds $t_w^{(sat)}$. Thus, this trade-off problem between delivered bits and handoff latency can be formulated to find an saturation network selection time "$t_w^{(sat)}$", i.e.,

$$\begin{aligned} t_w^{(sat)} = \arg_{0 \leqslant t_w \leqslant d_i - t_a} \{ & \frac{\partial}{\partial t_w} \{[P_{search}(t_w + t_a) \cdot S_{\text{WLAN}}(n_{11}) \\ & + (1 - P_{search}(t_w + t_a)) \cdot S_{\text{WiMax}}(n_{16})] \\ & \cdot (t_d - t_w - t_a)\} = \alpha\} \end{aligned} \tag{4.4}$$

where α is the derivative of delivered bits during the dwelling time t_d at $t_w^{(sat)}$.

4.2.2 Delivered information bits, $S(t_w)$

Next, we analyze the impact of network selection time t_w on the delivered information bits during the dwelling time t_d in the new "WLAN to WLAN/WiMax" handoff scenario. According to [28], given a period of time, t, we can obtain a successful search probability value in WLAN handoff, $P_{search}(t)$. Thus, the total delivered information bits "$S(t_w)$" in both WLAN and WiMax systems during the dwelling time t_d is given by

$$S(t_w) = g(t_a) \cdot (t_d - t_a - t_w) \cdot \ [P_{search}(t_a + t_w) \cdot S_{\text{WLAN}} + (1 - P_{search}(t_a + t_w)) \cdot \ S_{\text{WiMax}}] + (1 - g(t_a)) \cdot \ (t_d - t_a) \cdot S_{\text{WiMax}} \ , \tag{4.5}$$

where $P_{search}(t_a + t_w)$ is the success probability during the channel search time $t_a + t_w$ in WLAN; and

$$g(t_a) = \begin{cases} 1 \ , & \text{if } S_{\text{WLAN}}(n_{11}) \geq S_{\text{WiMax}}(n_{16}) \text{ after } t_a \\ 0 \ , & \text{otherwise} \end{cases} . \tag{4.6}$$

(1) Successful search probability, $P_{search}(t)$

In the previous work [28], we developed an analytical model for single channel search time t_b and its success probability $P_s^{(sc)}$ in the WLAN handoff. Here, we extend it for the overall channel search time t_s in WLAN, including x channels, and its success probability $P_{search}(t)$. Consider the situation that the station may successfully search at least one available AP in consecutively search y periods and each period contains x channels searching. Then, the channel search time t_s and its success probability P_{search} for y periods can be given by

$$\begin{cases} t_s(y) = t^{(mc)} \cdot y \\ P_{search}(y) = 1 - (1 - P_s^{(mc)})^y \end{cases} , \tag{4.7}$$

where $t^{(mc)}$ and $P_s^{(mc)}$ are the time and probability that the handoff station can successfully search at least one AP among the x channels, respectively. Since the channel condition and the probability of AP existing in each channel P_i are different. Therefore, $t^{(mc)}$ and $P_s^{(mc)}$ can be written as

$$\begin{cases} t^{(mc)} = \sum_{i=1}^{x} (P_i \cdot t_{b,\ i} + (1 - P_i) \cdot t_{nb}) \\ P_s^{(mc)} = 1 - \prod_{i=1}^{x} (1 - P_{s,\ i}^{(sc)} \cdot P_i) \quad , \end{cases} \tag{4.8}$$

where $t_{b,\ i}$ and $P_{s,\ i}^{(sc)}$ are the channel search time and successful search probability in the busy channel i, respectively; and t_{nb} is the channel search time in a idle channel [28].

(2) MAC throughput in the 802.11 WLAN, S_{WLAN}

In the considered scenario, the WLAN interface of mobile station follows the carrier-sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol in the 802.11 interface. From [10], we can have the MAC throughput $S_{\text{WLAN}}(n_{11})$ as

$$S_{\text{WLAN}}(n_{11}) = \frac{P_s \cdot P_{tr} \cdot E[P]}{(1 - P_s) \cdot P_{tr} \cdot T_c + P_s \cdot P_{tr} \cdot T_s + (1 - P_{tr}) \cdot \sigma} \ , \tag{4.9}$$

where T_s and T_c are the average time that the medium is busy due to a successful transmission or a collision, respectively. $E[P]$ is the average packet payload size; and σ is the duration of an empty slot; and P_s is the success probability of a frame transmission; and P_{tr} is the probability that at least one frame is transmitted. For further details of above parameters, see [10].

(3) MAC throughput in the 802.16e WMAN, S_{WiMax}

Note that when calculating MAC throughput [29], any control information, such as preamble, DL-MAP, UL-MAP, BW/RNG requests, DCD/UCD messages, TTG and RTG, and MAC protocol data unit(PDU) header, are all overhead. Hence, MAC throughput can be expressed as

$$S_{\text{WiMax}}(n_{16}) = \frac{total\_bits - overhead\_bits}{OFDMA\_frame\_time} \ , \tag{4.10}$$

Table 4.2: System Parameters

MAC throughput per user in WLAN [10]	4.25 Mbps (10 users) 1.22 Mbps (30 users)
MAC throughput per user in WiMax [30]	1.11 Mbps (50 users)
awakening time in WiMax	25 ms
number of channels in WLAN	3
MS moving speed	5 km/hr
WLAN coverage	100 m
dwelling time in target WLAN (t_d)	72 sec

where *total_bits* denotes the total number of bits transmitted in one TDD time frame, and *overhead_bits* denotes the number of bits that convey the control information.

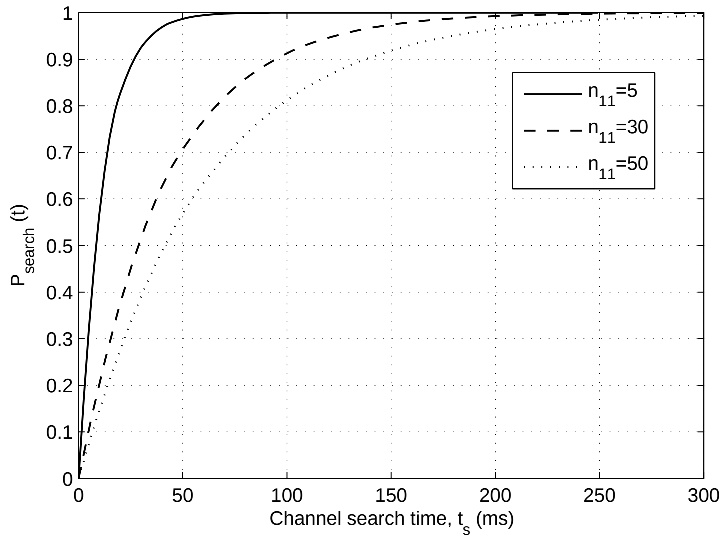
4.3 Numerical Results

In this section, first we show the comparison between channel search time in WLAN and awakening time in WiMax. Then, we examine the total delivered information bits during the dwelling time t_d by means of various network selection schemes. We also list the delivered information bits after waiting the network selection time "$t_w^{(max)}$" and "$t_w^{(sat)}$" with different number of stations. The considered network topology is shown in Fig. 1.1, where 50 stations locate in WMAN. A handoff station moves from one WLAN to another WLAN at the speed of 5 km/hr, and it looks for the AP among the three channels in WLAN. The coverage of a WLAN is 100 meters, and the WMAN covers both the two WLANs. Other related system parameters are shown in Table 4.2.

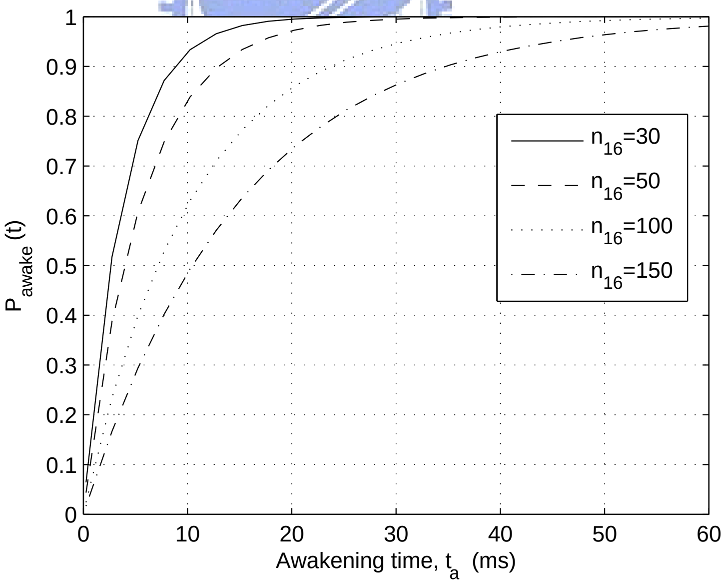
4.3.1 Success probability of channel search time and bandwidth request time in WLAN and in WiMax, respectively

Figure 4.4(a) shows the success probability of channel search time with various number of station in the 802.11 WLAN. From this distribution, we can realize the relationship between the increasing rate of successful search probability and number of existing station. As shown in the figure, the handoff station can achieve high success search probability, i.e. $P_{search} \geq 0.9$ in a short search latency, i.e. $t_s \approx 35ms$, as there are few existing stations, i.e. $n \leq 5$ in the target WLAN. However, when the number of station increase, the increasing rate of success handoff probability decrease due to the collision from the existing stations. Thus, the handoff station need more channel search time to achieve high success probability.

Furthermore, figure 4.4(b) shows the success probability of awakening time (bandwidth request delay), with various number of stations in the 802.16e WMAN [25] by allocating 16 sub-channels and 20 transmission opportunities in a OFDMA frame. In the figure, we find that success probability approach to one as bandwidth request time is only about $25ms$, even in the large number of station, e.g. $n_{16} = 50$. Compared to the channel search time in WLAN, the awakening time is 10 times smaller than channel search time in the same success probability. That means the WiMax system can complete the handoff process in a short time compare to that in the WLAN. Thus, as two system jointly vertical and horizontal handoff in "WLAN to WLAN/WiMax", generally WiMax will complete the awakening process first, i.e. $t_a < t_s$.

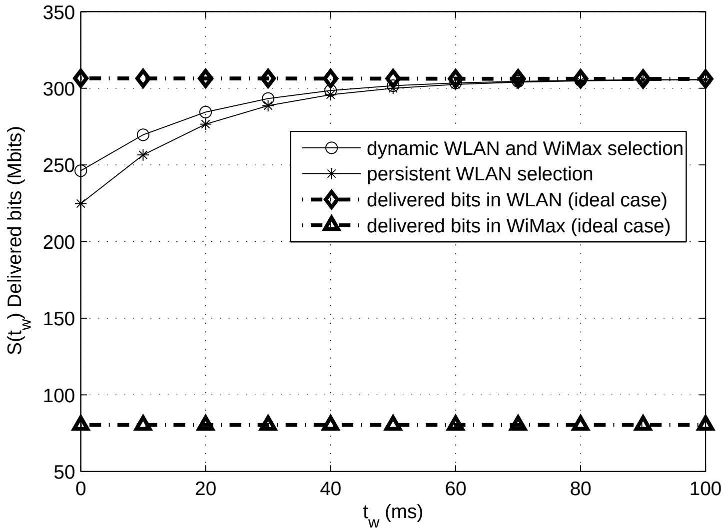


(a)

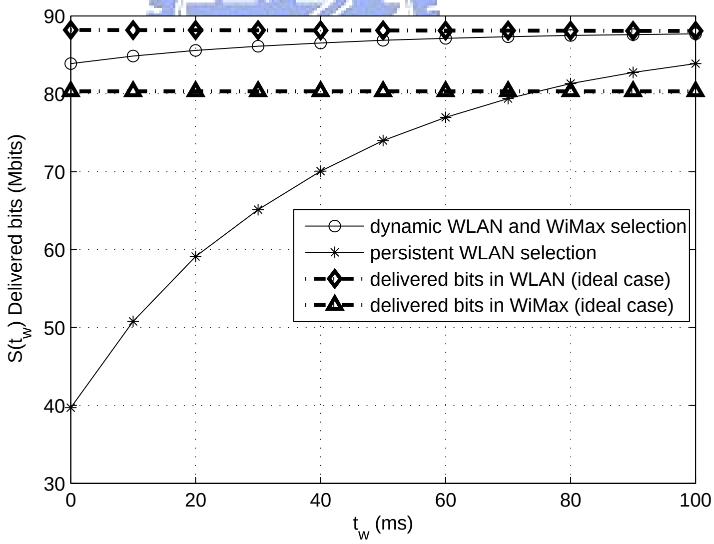


(b)

Figure 4.4: Comparison of success probability between(a)channel search time in WLAN and(b) bandwidth request delay in WiMax with various number of station



(a)



(b)

Figure 4.5: Comparison of the delivered bits during t_d between proposed and conventional schemes with (a)10 and (b)30 stations in the target WLAN, respectively.

4.3.2 Performance comparison between proposed and conventional schemes

Figure 4.5 shows the total delivered information bits during the dwelling time t_d versus various values for network selection time t_w with 10 and 30 stations in the target WLAN, respectively. The considered two network selection schemes are: (1) dynamic network selection among WLAN and WiMax; (2) persistent WLAN selection, i.e., the handoff station insists on connecting to the target WLAN. In addition, the figures also show the amount of delivered information bits if a station stays in WLAN and WiMax during the dwelling time t_d, respectively. As shown in Fig. 4.5(a), the dynamic selection scheme only improves 9% for the case of 10 stations in the target WLAN. Due to fewer contentions between the handoff station and others in the target WLAN, the handoff station can easily find an available AP and thus the improvement decreases. However, in the case with 30 stations, the proposed scheme improves almost by 100% compared to the "persistent WLAN selection" scheme, as shown in Fig. 4.5(b). In this situation, the target WLAN has low available throughput and the channel search time is long due to the increase of the contentions. Therefore, the dynamic selection scheme in the crowded WLAN outperforms than that in sparse WLAN.

4.3.3 Maximum and saturation network selection time

Figure 4.6 shows the impacts of the network selection time t_w on the delivered information bits. As shown in the figure, an maximum network selection time $t_w^{(max)}$ exists to enable the handoff station delivering maximum information bits during the dwelling time, t_d. As the network selection time t_w prolongs, the amount of delivered information bits increases due to the improvement of success probability for the channel search process. However, when the duration of t_w is too large, the amount of

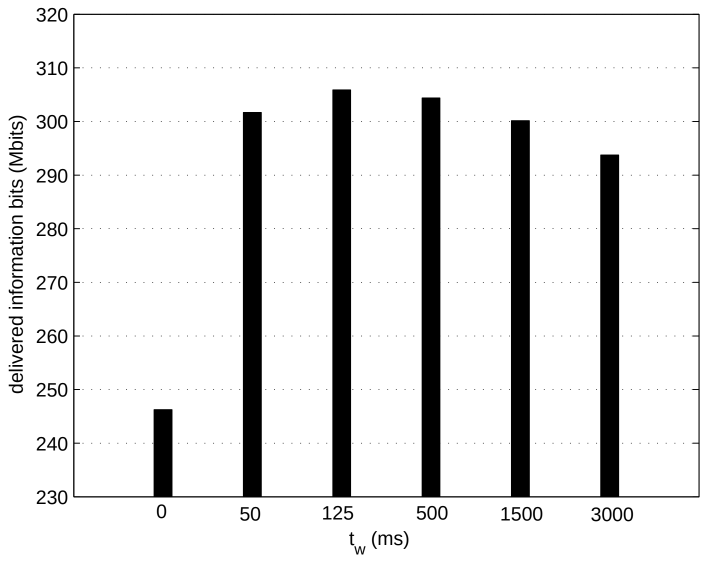


Figure 4.6: Delivered information bits versus the various network selection time t_w with 10 stations in the target WLAN

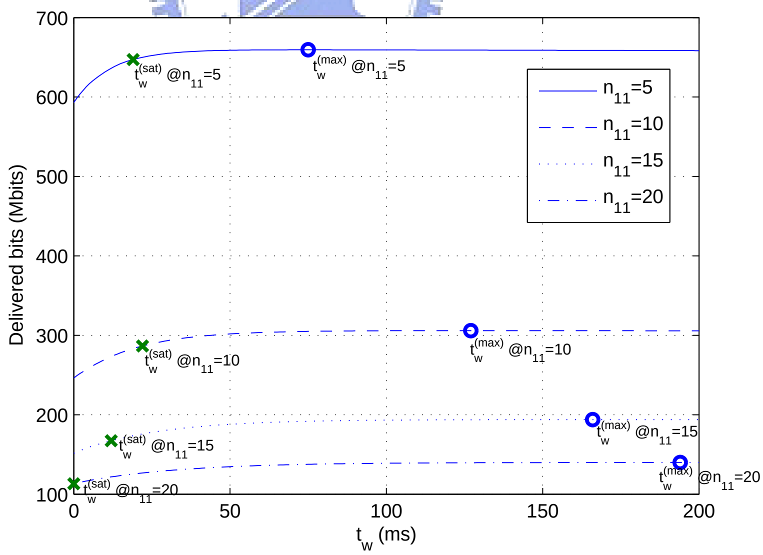


Figure 4.7: Comparison between maximum network selection time and saturation network selection time; $\alpha = 1$ $Mbits/ms$

Table 4.3: Maximum and saturation network selection time

number of stations n_{11}	maximum network selection time $t_w^{(max)}$ (ms) / delivered bits (Mbits)	saturation network selection time $t_w^{(sat)}$ (ms) / delivered bits (Mbits)
5	80 / 659	20 / 647
10	125 / 306	23 / 286
15	170 / 194	13 / 167
20	195 / 140	1 / 113

delivered bits saturates and even starts decreasing because of the long wasted time in channel search. In addition, we also find another network selection time, i.e. saturation network selection time $t_w^{(sat)}$ to solve the tarde-off between the delivered bits and handoff latency. Because it is not efficient to obtain few delivered bits improvement as the network selection time exceeds $t_w^{(sat)}$ as shown in Fig. 4.7. Thus, after waiting only an saturation network selection time $t_w^{(sat)}$, the handoff station can achieve almost maximum the delivered information bits during the dwelling time, t_d. Table 4.3 lists the values of the maximum network selection time $t_w^{(max)}$ and saturation network selection time $t_w^{(sat)}$ corresponding delivered bits with various numbers of stations, respectively.

4.3.4 Delivered bits improvement

Figure 4.8 shows the improvement of the delivered information bits at the maximum network selection time $t_w^{(max)}$ with various numbers of stations compared to that at $t_w = 0$. As shown in the figure, when $5 \sim 25$ stations locate in the target WLAN, the handoff station waiting for the maximum network selection time $t_w^{(max)}$ can deliver more information bits at least by 10%. However, in the sparse WLAN, e.g. 5 stations

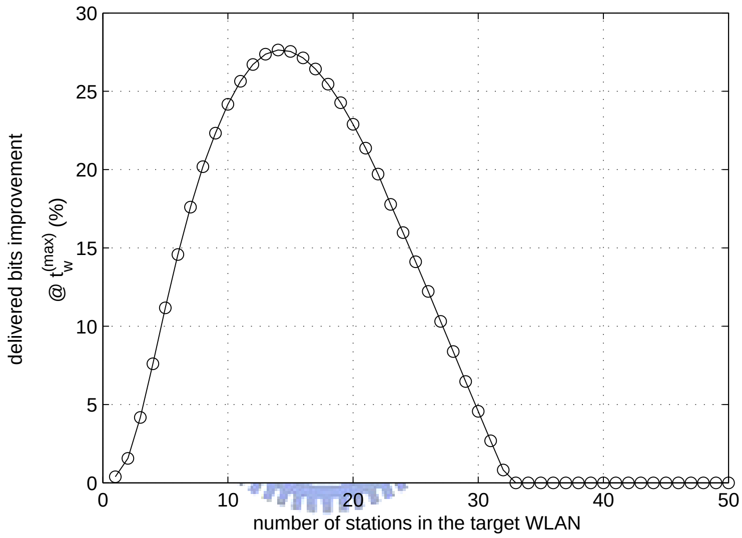


Figure 4.8: Improvement of delivered bits with maximum network selection time $t_w^{(max)}$ versus number of stations in the target WLAN

in the target WLAN, the improvement is small due to the high successful channel search probability. On the other hand, as the network is more crowded, e.g., more than 30 stations, the handoff station does not need to search the WLAN because the available throughput in WLAN is smaller than that in WiMax.

4.4 Conclusions

In this paper, we identify a new "WLAN to WLAN/WiMax" handoff scenario. Next, a dynamic WLAN/WiMax network selection scheme is proposed to maximize the delivered information bits during the dwelling time t_d in a new "WLAN to WLAN/WiMax" handoff scenario. The proposed scheme requests the handoff station waiting a short network selection time t_w to maximize the delivered bits during the dwelling time t_d before selecting the target networks. We also formulate the optimization problems to maximize the delivered bits by waiting the maximum network selection time $t_w^{(max)}$ and optimize the delivered bits and handoff latency by waiting saturation network selection time $t_w^{(sat)}$.

CHAPTER 5

Conclusions and Future Research Suggestions

There are two major contributions in this thesis. First, we propose an analytical model to evaluate the single and multiple channel search time and its success probability in the IEEE 802.11 WLAN handoff. Before this model was proposed, many studies analyze the handoff latency in WLAN by measurement in practice. In addition, by minimizing two new performance metrics, "*single channel effective search time,* $t_{eff}^{(sc)}$" and "*multiple channel effective search time,* $t_{eff}^{(mc)}$", the handoff station can obtain the optimal handoff parameters and experience the minimum latency during the handoff occurs. Second, we develop a network selection scheme in the new "WLAN to WLAN/WiMax" handoff scenario to determine which system has the most delivered information bits during the dwelling time t_d. The proposed scheme requests the handoff station waiting for a short network selection time t_w before selecting the networks. We formulate an optimization problem to find the maximum network selection time "$t_w^{(max)}$" for maximizing the delivered bits. In addition, we also find the saturation network selection time "$t_w^{(sat)}$" for optimizing the delivered bits and handoff latency during the dwelling time.

5.1 Optimal Handoff Channel Search Time for Wireless Local Area Networks

In Chapter 3, we derive a close-form expression for the channel search time and its success probability for 802.11 handoff in terms of number of stations and system parameters. Form analytical model, the handoff station can obtain the optimum numbers of probe request/response transmissions during the handoff occurs in various constraints, such as low search latency or high successful search probability. Furthermore, by minimizing two new performance metrics, "*single channel effective search time,* $t_{eff}^{(sc)}$" and "*multiple channel effective search time,* $t_{eff}^{(mc)}$", the handoff station can experiences the minimum latency during the handoff occurs by the optimal handoff parameters. From the numerical result demonstrate that, in the case with 100 stations, the single and multiple channels effective search time with optimum number of transmissions can be reduced by 30% and 40% compared to the legacy IEEE 802.11 WLAN, respectively.

5.2 Network Selection with Joint Vertical and Horizontal Handoff in the Heterogeneous WLAN and Mobile WiMax System

In Chapter 4, we focus on a new "WLAN to WLAN/WiMax" handoff scenario, and suggest a dual-interface station has to wait for a short duration before selecting the networks even if one of the network interfaces successfully establishes a new connection. By this way, the handoff station can maximize the delivered information bits during the dwelling time in the target network. From the numerical results, in the case with 5 $\sim$ 25 stations in the target WLAN, the proposed scheme can improve the delivered bits at least by 10% compared to that without awaiting the additional network selection time.

5.3 Suggestions for Future Research

For the future research, we provide the following suggestions to extend our work:

- The impact of the wireless channel on the proposed analytical model and algorithm.
- The impact of the delay overhead from Mobile IP on the proposed network selection scheme between 802.11 WLAN and 802.16e WMAN.
- In order to accurately obtain the optimal network selection time "t_w^*", the MAC throughput in 802.11 WLAN and 802.16e WMAN shall be more accurate, such as the impacts on the transmission distance and throughput allocation in the 802.16e WMAN.

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