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How DHCP Leases Meet Smart Terminals: Emulation and Modeling

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***Abstract*—DHCP provides dynamic use of IP addresses, but it presents challenges to meet smart terminals with great mobility and transient network access patterns. Existing studies have tried to solve this problem through adjusting DHCP *lease*, which controls how long a host owns an address. However, few studies clearly express the relations among the lease, address utilization and DHCP overhead.**

In this paper, we uncover how the leases affect address utilization and DHCP overhead with two methods, based on which, we can set the leases for the smart terminals flexibly and judiciously. First of all, we present an emulation technique to evaluate address utilization and DHCP overhead under different leases. It provides an experimental basis for setting the lease for the whole WLAN. Evaluation results show that if the lease is set to 120 minutes instead of 60 minutes by default, it can reduce 41.78% DHCP overhead on average and still reserve at least 9.2% address space for the possibly emerging terminals. Then, we model the relationship between the lease and address utilization, as well as the relationship between the lease and DHCP overhead. According to these models, we propose a load-aware DHCP lease time optimization algorithm, which helps to set different leases for each area of the WLAN based on theoretical analysis. Evaluation results show that compared with the default lease for the whole WLAN, a lease combination of {15, 120, 120} for different areas can reduce 36.85% DHCP overhead on average and guarantee there is always 10% available address space.

***Index Terms*—mobile computing, network protocols, DHCP, smart terminals, lease time.**

I. Introduction

THE Dynamic Host Configuration Protocol (DHCP) [1] is used to assign and reclaim IP addresses to and from clients automatically. It can preserve scarce address space if the parameters are properly configured at the DHCP server. One of the most critical parameters is the *lease time*, which determines the validity duration of an allocated address in one request period. If a DHCP server does not receive a request message form a client within the lease time, it will reclaim the IP address from the client when the lease expires. Through this mechanism, inactive addresses can be reclaimed to the address pool and assigned to other clients, which enhances the efficiency of address utilization.

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In the PC-dominant periods, a host usually uses an address for a long period of time. DHCP leases are easy to satisfy the needs of such user online patterns, which are stable in most cases. However, in the era of smart terminals, users are more likely to move from one place to another. A client may use an address in one place for a short time, and need to apply for a new address in a place of another. In addition, a user may hold many smart terminals, such as phone, pad, watch, etc. This aggravates the increasing demand on transient IP addresses. Due to the predictable exhaustion of IPv4 addresses [2], more and more WLANs will not have enough IP addresses to serve the increasing smart terminals. Therefore, pursuing high efficiency of address utilization is necessary for the WLANs with scarce addresses, because it could reduce the chance that a terminal in a scarce address pool cannot get an address. However, how to judiciously set the leases to adapt to the transient network access patterns is a challenging problem. Large lease time may cause the inactive addresses to survive in the network for a longer but meaningless period of time. Most clients do not send release messages to DHCP server, and the addresses allocated to these terminals cannot be reclaimed until the leases expire, which accelerates the exhaustion of a scarce address pool. Small lease can reduce the inactive addresses surviving time, and the allocated address can be reclaimed efficiently. But small lease will introduce substantial DHCP broadcast traffic to the network, as well as result in unnecessary activation of the wireless interfaces by power limited devices [3]. In this paper, we focus on how DHCP leases meet smart terminals. The challenges of determining proper leases for a WLAN include the following two aspects.

(1) How the leases affect address utilization and DHCP overhead, and how to express the relationship between address utilization and DHCP overhead. Ideally, both address utilization and DHCP overhead should be reduced. However, we have to optimize one aspect without considerably sacrificing another by adjusting the lease. There are no criteria to judge how much DHCP overhead the optimization should sacrifice to the address space or vice versa. Therefore, it needs to express the relationship between address utilization and DHCP overhead. Given an address utilization, we should evaluate how much DHCP overhead will be generated under different lease time settings. Also, given a DHCP overhead, we should evaluate how large an address space is needed under different lease time settings.

(2) How DHCP leases cope with the transient network access patterns. In the era of smart terminals, user mobility increases the demand of transient IP addresses. In addition,

the demand is hard to predictable. So it is wise to adjust the lease according to the real requirements of a WLAN. We need a flexible lease time setting method to meet the transient network access patterns. For example, if the address pool of a WLAN is scarce, we can control the address utilization under a threshold and guarantee that the address pool can satisfy the needs of the burst of online users. In addition, we also know how much DHCP overhead will be introduced when the threshold is given, then we can easily make the tradeoff between address utilization and DHCP overhead.

Existing studies have tried to optimize DHCP leases according to terminal types [3] or user online patterns [4]. They focus on improving address utilization at the expense of DHCP overhead, or reducing DHCP overhead at the expense of address utilization. In this paper, *DHCP overhead (load)* is defined as the control messages that are transmitted to the network and processed by DHCP server and clients. Although the DHCP load cannot overload the links, it can increase the overhead of the DHCP server, and introduce unnecessary traffic sent to the terminals [3, 4]. So DHCP load should be reduced as much as possible. It has to sacrifice one aspect for another during the optimization. However, there is no specific criterion to say which aspect is more crucial, and few studies clearly express the relations among the lease, address utilization and DHCP load.

Different from previous studies, we uncover how the leases affect the address utilization and the DHCP load, based on which, we optimize the lease time on the premise of reducing the DHCP load as much as possible while control the address utilization under a threshold. That is to say, given a WLAN and its terminals' online patterns, we can accurately depict the address utilization and DHCP load under different lease time settings. So our methods could determine proper leases to meet the smart terminals with the demand on transient IP addresses. The main contributions are summarized as follows.

(1) We propose an emulation technique to evaluate address utilization and DHCP load under different lease time settings. We divide the users into three different groups, including *access user*, *disconnection user* and *online user*. According to this division, we can infer the number of address that will be used and the number of DHCP messages that will be generated. Evaluation results show that if we adjust the lease from the default 60 minutes to 90 minutes, we can reduce 41.78% DHCP load on average but still reserve at least 9.2% address space.

(2) We model the user behaviors, including session length distribution, address usage time distribution, and departure time distribution, etc. Then we use these models to depict the relationship between address utilization and the lease time, as well as the relationship between DHCP load and the lease time. Evaluation results show that the models have good fitness and can reveal how the lease affects the address utilization and DHCP load when it is set to different values.

(3) We propose a load-aware DHCP lease time optimization algorithm to determine a lease combination with the objective of minimizing the DHCP load while controlling the address utilization under a threshold to satisfy the burst of online users. Evaluation results show that if we choose the lease combination of {15, 120, 120} for different areas of the studied WLAN, we can reduce 36.85% DHCP load on average and guarantee there is at least 10% of the address space that can be utilized.

This paper conducts a case study on how DHCP leases meet smart terminals based on the data gathered from a campus WLAN. However, both the emulation technique, models and the optimization algorithm are applicable to any WLAN if related data can be provided. That is to say, our work can be used to any WLAN adopting DHCP to manage the IP address pool.

The remainder of this paper is organized as follows. Related work is presented in Section II. The background and dataset are presented in Section III. The emulation technique used to evaluate address utilization and DHCP load under different lease time settings is described in Section IV. Section V models the relationship between address utilization and the lease. Section VI models the relationship between DHCP load and the lease. Section VII shows the flexible lease time optimization algorithm and Section VIII evaluates the proposed algorithm. Section IX concludes the whole paper.

II. Related Work

Related work is presented from two aspects. We begin with discussion of existing works on understanding user (terminal) behaviors. Then, we show the studies that have been conducted on DHCP performance analysis.

A. Understanding User Behaviors

With the explosive increase of mobile terminals, there are many works understanding user (terminal) behaviors. C. Tuduce et al. [5] proposed a framework to analyze mobility characteristics of a WLAN and designed a model to simulate mobility scenarios based on the characteristics. W. J. Hsu et al. [6] put forward a time-variant community mobility model to uncover time dependent behaviors and reveal the periodic reappearance of terminals at specific locations. H. Falaki et al. [7, 8] analyzed the traffic of smartphones and the diversity of smartphone usages. A. Gember et al. [9] investigated the characteristics of handheld and non-handheld devices through analyzing the traces of two campus wireless networks. J. Kim et al. [10] investigated the evolution of user mobility of a WLAN and designed several predictors using Markov chains of different orders. X. Chen et al. [11] measured the network performance of smart mobile handheld devices and investigated the dominant factors that affect the network performance. W. J. Hsu et al. [12] analyzed user association patterns of a campus WLAN through leveraging clustering techniques. X. Chen et al. [13] modeled the number of concurrent IP addresses and analyzed the effect of session length distribution and user's arrival rate on IP address utilization. U. Kumar et al. [14] compared the mobility characteristics of smartphones with laptops in a campus WLAN. S. C. Geyik et al. [15] analyzed the mobility patterns of a WLAN and modeled the mobile behavior using the probabilistic context-free grammar. T. Wang et al. [16] captured the statistical user mobility patterns using the mobility graph. N. Cruz et al.

[17] investigated the evolution of user behaviors over time through analyzing the user access records. A. K. Das et al. [18] characterized the usages of multiple-device users, as well as the usages of different device types.

In this paper, we model the user (terminal) behaviors of a campus WLAN, including session length distribution, address usage time distribution, and departure time distribution, etc. Different from previous studies, we use these models to reveal the relations among address utilization, DHCP load and the lease time. In other words, user behaviors provide the basis for analyzing DHCP performance and optimizing the lease time.

B. Analyzing DHCP Performance

DHCP [1] enables terminals to request IP addresses and networking parameters automatically, which reduces the need for a user to accomplish the process manually. Many aspects about DHCP performance are explored combining with user behavior analysis and modeling, including DHCP usages, DHCP lease settings and DHCP churn, etc. I. Papapanagiotou et al. [3] investigated the impact of the new types of device on DHCP. They found that DHCP implementation varies among device types and has an effect on DHCP lease durations. Then they proposed a lease setting method taking device types into account. M. Khadilkar et al. [4] analyzed the effect of different lease time settings and proposed two dynamic lease time optimization strategies, including the single adaptation strategy and the exponential adaptation strategy. A. K. Das et al. [18, 27] observed how current DHCP configurations are oblivious to multiple devices and pointed out that a shorter lease time for the hand-held devices could improve the efficiency of address space utilization. V. Brik et al. [19] designed a DHCP-Watch to evaluate the performance and vulnerabilities of DHCP. They first pointed out that setting the lease duration could affect DHCP performance. T. V. Do [20] proposed a retrial queuing model to approximate the performability of the DHCP dynamic allocation mechanism and analyzed the impact of the lease time on it. S. Seneviratne et al. [21] found that the IP address acquisition time accounts for 80% of the total connection setup time and the IP address acquisition delay is mainly caused by the losses of DHCP messages at the WiFi access point. L. Vu et al. [22] investigated the impact of hosts changing IP addresses (referred to as DHCP churn) on analyzing DNS, firewall alert and Netflow data. G. Moura et al. [23] built a statistical model to estimate ISP and Internet-wide DHCP churn rates. X. Wei et al. [24, 28] profiled the behaviors of hand-held devices and found that 68% devices issue unnecessary lease requests, which may be caused by software bugs [25]. They also pointed out that a differential group-based IP allocation strategy is necessary.

Existing studies have been conducted on DHCP usage patterns and lease time optimization. They reduce address utilization while introducing more DHCP load, or reduce D-HCP load while using more addresses. Different from previous studies, we emulate DHCP activities, model user behaviors, and reveal the relationship between the lease time and IP address utilization, as well as the relationship between the lease time and DHCP load. Therefore, we are able to capture the address utilization patterns and corresponding DHCP load under different lease time settings. Then, we can not only set the lease to the whole WLAN with the straightforward emulation technique, but also determine the leases for different areas of the WLAN based on the models and algorithm. This will perfectly cope with the transient network access pattern-s. Compared with some existing client-granularity methods, which need to maintain the state of each terminal and introduce too much overhead to the DHCP server, the proposed area-granularity method is more applicable to set the leases for a WLAN.

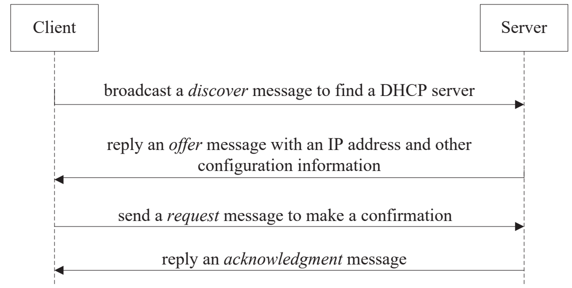


Fig. 1. The process of a client getting an IP address from DHCP server.

III. BACKGROUND AND DATASET

In this section, we first take a look at the DHCP background for the sake of latter presentation. Then we describe the dataset used in this study.

A. Overview of DHCP

DHCP makes hosts get the IP address, subnet mask, default gateway, etc., without human participation. With the increasing of smart terminals, users are more likely to move from one place to another. DHCP can dynamically allocate addresses to clients, which can accommodate the user mobility gracefully. As specifications of DHCP [1], DHCP has four essential types of messages, including *discover* message, *offer* message, *request* message and *acknowledge* message. As depicted in Fig. 1, after the interaction between the client and DHCP server, DHCP server allocates an IP address to a client for a period of time, which is called a *lease*. This IP address can't be allocated to new connected clients before it is released by the client actively or the lease expires. If the client is still active and reaches to half of the lease time, it will send a *request* message to the DHCP server to renew its lease.

When a client leaves the network, it may send a *release* message to the DHCP server. After receiving the *release* message, the server will release the lease, and the IP address can be allocated to new connected clients. If the client does not send a *release* message to the DHCP server, the IP address previously used by the client cannot be allocated to other clients until the lease expires.

B. Description of Dataset

Our data is collected from a campus WLAN. The network contains 918 wireless Access Points (APs), which are dis-

TABLE I
THE NUMBER OF APS IN EACH AREA

No.	Area	The number of APs
1	Biology Technology Building	75
2	Liberal Arts Building	93
3	Life Service Center	39
4	Information Technology Building	44
5	Dormitory	667

tributed in 5 areas, including Biology Technique Building, Liberal Arts Building, Information Technology Building and Dormitory. The APs are controlled by two wireless Access Controllers (ACs). There is one DHCP server being charge of the address allocation and reclamation. We collected the logs of the DHCP server and ACs from June 15th to July 15th in 2016. Logs of ACs are gathered through SNMP at the scale of every five minutes. The DHCP server logs record the addresses which are being used. And the AC logs record the information of each AP and their associated terminals, including MAC address, IP address, sending and receiving data size, Received Signal Strength Indicator strength, etc. In this paper, the data we extracted from AC logs is the association relationship between a terminal and an AP, denoted by *Association_Rec* = (*User_MAC*, *AP_MAC*, *Timestamp*). A record represents that a terminal with the *User_MAC* was associated with an AP with the *AP_MAC* at the time of *Timestamp*. We use such consecutive records to estimate the user online session length.

Table I shows the number of APs in each area. In the studied WLAN, the size of the IP address pool is 4050, and the default lease time is 60 minutes. According to the logs of ACs, we calculate the session length distribution of the studied WLAN. As depicted in Fig. 2, more than 40% sessions are shorter than 60 minutes, and more than 60% sessions are shorter than 120 minutes. We also find that only fewer than 10% sessions are longer than 480 minutes. Session length distribution provides guidance for DHCP lease time setting. For example, if there are enough available addresses, we may set the lease time to 480 minutes. The lease can satisfy most terminals and meanwhile introduce fewer DHCP messages. However, the studied WLAN is address hungry and most terminals omit releasing the leases when the sessions terminate. In this case, the assigned addresses cannot be reclaimed until the leases expire and a large lease will promote the short sessions to exhaust the address space. So it is wise to make a balance between address utilization and DHCP load. That is to say, the lease should avoid exhausting the address space in order to satisfy the burst of arrival users, and reduce the influence on the DHCP server and the terminals caused by DHCP load.

IV. AN EMULATION TECHNIQUE

With the increasing smart terminals, it is crucial to choose a proper DHCP lease time to meet the transient user access patterns caused by user mobility. But it is very hard to evaluate which lease time is better to cope with the requirements. In this paper, we propose an emulation technique to evaluate the address utilization and DHCP load according to user status. With this technique, we can evaluate the address utilization and corresponding DHCP load under different lease time settings.

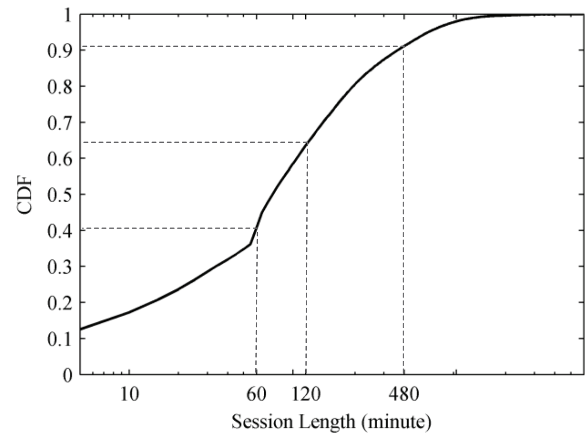


Fig. 2. Session length distribution of the studied WLAN.

To our best knowledge, there are no studies to evaluate how the leases affect the address utilization and DHCP load based on user status.

We classify the users into three sets at each time point, including *access user set (AUS)*, *disconnection user set (DUS)* and *online user set (OUS)*. The consecutive association records are used to classify the user status. 1) A user is online at the current time point, while was offline at the previous time point, the user is a new access user and classified into the set of *AUS*; 2) A user was online at the previous time point, while is offline at the current time point, the user is a departure user and classified into the set of *DUS*; 3) A user keeps online at two consecutive time points, the user is classified into the set of *OUS*. According to the division of user status and DHCP specifications [1], we design a series of rules to evaluate DHCP load.

1) For users in AUS: On the one hand, if a user needs to apply for an IP address, which means the user has never accessed to the network, or the lease of the user's client has expired, or the client has released the lease when the user leaving the network, the number of *discover* message, the number of *offer* message, the number of *request* message and the number of *acknowledge* message will increase by one respectively. Then the lease of the client will be set to the entire lease time. On the other hand, if a user has no need to apply for an IP address, which means the user omitted releasing the lease and the lease is still active, the number of *request* message and the number of *acknowledge* message will increase by one respectively. Then the lease of the client will be updated to the entire lease time.

2) For users in DUS: If the lease of a client is released actively, the number of *release* message will increase by one and the lease time will be set to 0.

3) For users in OUS: If the lease of an active client reaches to half the lease time, the client needs to extend the lease. The number of *request* message and the number of *acknowledge* message will increase by one respectively. The lease of the client will be updated to the entire lease time.

Algorithm 1 describes how to calculate the DHCP load under a given *lease* at each time point. The *userSet* refers to the users captured at a time point. The *timeslice* is the data aggregation time scale and the value is 5 minutes in our study. We first classify the users into different user sets according to their status (line 1). Then we calculate the DCHP load of the users in AUS (line 2-10), DUS (line 11-16), and OUS (line 17-23) respectively.

Algorithm 1 Calculate DHCP Load under a Given Lease

```
Input: userSet, lease, timeslice
Initialization: timeslice ← 5, dhcpLoad ← 0
Function getDHCPLoad (userSet, lease, timeslice)
1: Classify the users in userSet into AUS, DUS, and OUS;
2: for each user in AUS do
3:     if the user needs to apply for an IP address then
4:         dhcpLoad ← dhcpLoad+4;
5:         user.lease ← lease;
6:     else
7:         dhcpLoad ← dhcpLoad+2;
8:         user.lease ← lease;
9:     end if
10: end for
11: for each user in DUS do
12:     if the user releases the lease then
13:         dhcpLoad ← dhcpLoad+1;
14:         user.lease ← 0;
15:     end if
16: end for
17: for each user in OUS do
18:     user.lease ← user.lease - timeslice;
19:     if user.lease ≤ half of the lease then
20:         dhcpLoad ← dhcpLoad+2;
21:         user.lease ← lease;
22:     end if
23: end for
24: return dhcpLoad
```

According to the user status classification, we can also calculate the number of IP addresses being used at each time point. We construct the user set of *occupying IP addresses (OIA)* according to the following two rules.

1) *For users in AUS and OUS, add them to OIA at the current time point;*

2) *For users in DUS who omit releasing the leases, add them to OIA at the current time point and keep them in OIA for some subsequent time points until the leases expire.*

Thus, the number of users in *OIA* equals to the number of IP addresses being used. ***Algorithm 2*** describes how to calculate the address utilization based on the user status division at each time point. Up to now, both DHCP load and address utilization at each time point can be calculated. We extract user status from the logs of ACs from June 15th to June 19th to evaluate the emulation technique. Fig. 3 shows the peak address utilization and DHCP load under different lease time settings during the whole observation. With the increase of the lease time, the address utilization increases, while the DHCP load decreases. If the lease is set to 60 minutes, the terminals require up to 3213 addresses, while only generate 1908 DHCP messages. Since not all the terminals need to apply for a new address or extend the lease, fewer DHCP messages are generated compared with the used IP addresses. If the lease is set to 90 minutes instead of 60 minutes, it can also provide available addresses to cope with the burst of online users. And the maximum DHCP load can be reduced by 10.48% at the cost of increasing 8.37% of the address utilization. If the lease is set to 120 minutes, the maximum DHCP load decreases below 1500 and the peak address utilization increases to 3676, which accounts for 90.8% of the total available addresses.

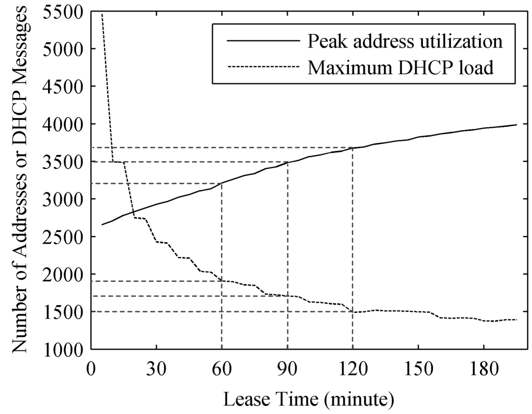


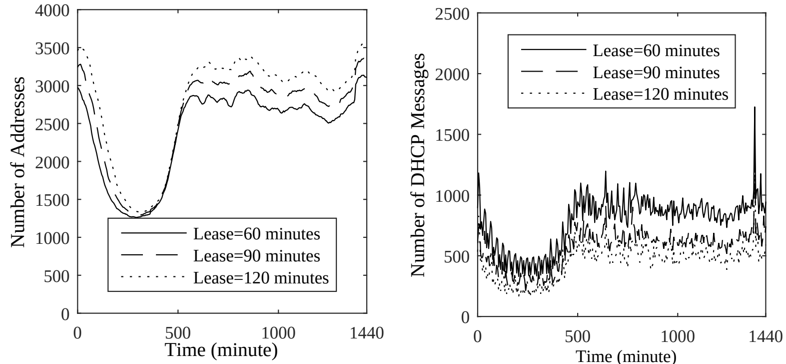
Fig. 3. Peak address utilization and maximum DHCP load of different leases.

Algorithm 2 Calculate Address Utilization Based on User Status

```
Input: AUS, DUS, OUS, timeslice
Initialization: timeslice ← 5, addressUtilization ← 0
Function getAddressUtilization (AUS, DUS, OUS, timeslice)
addressUtilization ← addressUtilization + sizeof(AUS);
addressUtilization ← addressUtilization + sizeof(OUS);
for each user in DUS do
    if user.lease ≠ 0 then
        addressUtilization ← addressUtilization+1;
        user.lease ← user.lease - timeslice;
    end if
end for
return addressUtilization
```

As depicted in Fig. 3, we also find that with the increase of the lease time, the maximum DHCP load decreases quickly at the beginning while gradually becomes stable at the level of 1500. So setting the lease to 120 minutes is a better choice to make the balance between address utilization and DHCP load. Fig. 4 shows the comparison results under the leases of 60 minutes, 90 minutes and 120 minutes in one day. From 60 minutes to 90 minutes, the DHCP load decreases 27.74% on average and the address utilization increases 8.01% on average. From 90 to 120 minutes, the DHCP load decreases 19.44% on average and the address utilization increases 7.17% on average. If the lease is set to 120 minutes, it can reduce the DHCP load by 41.78% on average at the cost of increasing 15.75% of the address utilization on average, but reserving at least 9.2% address space for the burst of arrival terminals.

In summary, the proposed emulation technique provides a basis for DHCP lease time optimization. With this straightforward method, we can observe the variations of address utilization and DHCP load under different lease time settings. So we can optimize the lease to meet the smart terminals according to the requirements of the studied WLAN. However, this technique is based on experimental observation, which lacks theoretical support. Therefore, we then create a series of models to reveal the relations among the lease, address utilization and DHCP load.



(a) Address utilization for different leases (b) DHCP load for different leases

Fig. 4. Address utilization and DHCP load under different lease time settings.

V. Relationship Between Address Utilization and the Lease

To further reveal the relationship between address utilization and the lease time, we first model the address utilization according to user behaviors.

A. Session Length Distribution

We use *three-stage hyper-exponential distribution* to model the session length distribution of the studied WLAN. The density function is represented as equation (1).

$$f(x) = \mu_1 p_1 e^{-\mu_1 x} + \mu_2 p_2 e^{-\mu_2 x} + \mu_3 p_3 e^{-\mu_3 x} \tag{1}$$

In equation (1), $\mu_1 > 0$, $\mu_2 > 0$, $\mu_3 > 0$, $p_1, p_2, p_3 \in [0, 1]$ and $p_1 + p_2 + p_3 = 1$. We use the following iterative method to determine the values of these parameters [26].

Given a set of points $\{c_1, c_2, c_3\}$, we divide the range of the interest into exponentially related sub-ranges under the restriction of $c_3 < c_2 < c_1$. Among these points, c_1 represents the point which is the most of interest, and c_3 represents the point which is the least of interest. The value of c_i/c_{i+1} is set to a constant of c. In our model, $c = \sqrt{c_1/c_3}$ and $c_2 = c \times c_3$. Let $q = \sqrt{c}$, where qc_1 should not be larger than the point with the highest interest.

Initially, we match the first phase (i.e., $i = 1$) to the tail of the given data. In other words, we have $\bar{F}_1(x) = \bar{F}(x)$, where $\bar{F}(x)$ is the CCDF of the session length. In general, in step i, we match the i_{th} phase to the tail of the remaining $\bar{F}(x)$. Each exponential phase has two parameters, i.e., p_i and μ_i. To find values for p_i and μ_i, we match $\bar{F}_i(x)$ at the points of c_i and qc_i. For the first phase and second phase (i.e., $i = 1, 2$ and $p_1 + p_2 < 1$):

$$p_i = \bar{F}_i(c_i) e^{\mu_i c_i} \tag{2}$$

$$\mu_i = \frac{1}{(1-q)c_i} \ln \frac{\bar{F}_i(qc_i)}{\bar{F}_i(c_i)} \tag{3}$$

where

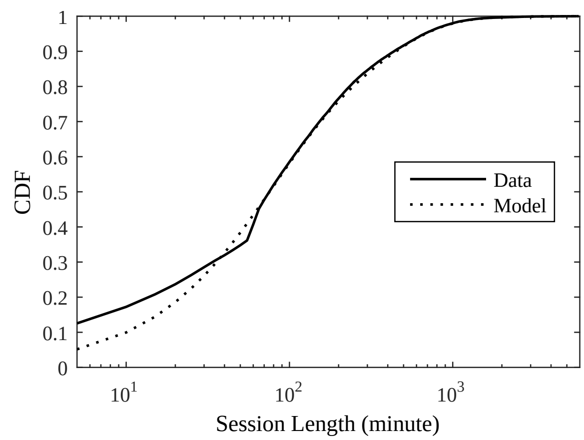


Fig. 5. Modeling results of the session length distribution.

$$\bar{F}_i(c_i) = \bar{F}(c_i) - \sum_{j=1}^{i-1} p_j e^{-\mu_j c_{j+1}} \tag{4}$$

$$\bar{F}_i(qc_i) = \bar{F}(qc_i) - \sum_{j=1}^{i-1} p_j e^{-\mu_j q c_{j+1}} \tag{5}$$

For the third phase (i.e., $i = 3$), to satisfy $p_1 + p_2 + p_3 = 1$, the computation method is different from the first two phases. We calculate p_3 and μ_3 according to equation (6) and equation (7).

$$p_3 = 1 - p_1 - p_2 \tag{6}$$

$$\mu_3 = \frac{-1}{c_3} \ln \frac{\bar{F}_3(c_3)}{p_3} \tag{7}$$

As a matter of fact, c_1 and c_3 affect the modeling results greatly. To determine the proper values for c_1 and c_3, we traverse all the possible combinations of c_1 and c_3. We find that when $c_1 = 588$ and $c_3 = 57$, the model has the smallest residual error of 0.021. Fig. 5 shows the modeling results compared with the real data. Results reveal that the session length distribution model has a good fitness.

B. Address Usage Time Distribution

Based on the session length distribution model, we can model the address usage time distribution. Three factors influence the address usage time: 1) a terminal releases the lease immediately when it leaves the WLAN. The occupied address is reclaimed by the DHCP server; 2) the terminal does not release the lease and the occupied address cannot be reclaimed until the lease expires; 3) the terminal is still active and the lease is extended when the remaining lease reaches to half of the entire lease. The density function of the address usage time can be represented by equation (8).

$$h(y, L_1, ..., L_N) = \sum_{d=1}^{N} h_d(y, L_d) \quad (8)$$

Where

$$h(y, L_d) = \{\sum (1-\beta)\cdot D(x,d)\cdot f(x) | x + L_d - x\%(L_d/2) = y\} + \beta \cdot D(x,d) \cdot f(y) \quad (9)$$

In equation (8), N is the number of areas of a WLAN and $h_d(y, L_d)$ is the address usage time distribution in area d. Session length usually presents different patterns across the areas (shown in Section VII). So we consider such differences when setting the leases for each area. In equation (9), $f(x)$ is the density function of session length, and β is the proportion of the terminals that release the leases immediately when they leave the WLAN. Through statistics, the value of β is 0.013 in our study. L is the length of the lease, and L_d is the lease time in area d. $D(x, d)$ represents the proportion of sessions with the length of x in area d.

C. Address Utilization

Based on the model of address usage time distribution, we can model the address utilization at each time point. Address utilization at time x is represented by equation (10).

$$M(x, L_1, ..., L_N) = \Lambda(x) - \sum_{t=1}^{x} h(x-t, L_1, ..., L_N)\Lambda(t) \quad (10)$$

Where

$$\Lambda(x) = \sum_{t=1}^{x} \lambda(t) \quad (11)$$

In equation (10), $h(x-t, L_1, ..., L_N)$ is the density function of address usage time when the lease is set to $L_1, ..., L_N$ for different areas. In equation (11), $\lambda(x)$ is the number of arrival terminals at time x. We use SRE (studentized residual) to evaluate the accuracy of the address utilization model. As shown in equation (12), e_i is the residual which is defined as equation (13). According to the property of residual in equation (14), we can calculate the studentized residual using equation (15). If the studentized residual of a modeling value is outside the interval of [-3, 3], the value is regarded as an outlier.

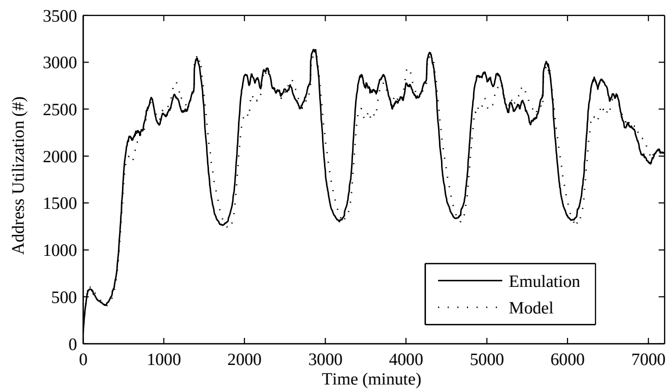


Fig. 6. Modeling and emulation results of the address utilization.

$$SRE_i = \frac{e_i}{\hat{\sigma}\sqrt{1-h_u}} \quad (12)$$

$$e_i = y_i - \hat{y}_i \quad (13)$$

$$var(e_i) = [1 - \frac{1}{n} - \frac{x_i - \bar{x}}{L_{xx}}] \times \sigma^2 \quad (14)$$

$$SRE_i = \frac{e_i \times \sigma}{\sqrt{var(e_i)} \times \hat{\sigma}} \quad (15)$$

Fig. 6 shows the modeling and emulation results of address utilization under the default lease of 60 minutes. We find that modeling results present similar patterns with the emulation results during the one week observation. We calculate the SRE for the modeling results. All the values of the studentized residual locate in the interval of [-3, 3]. The average absolute studentized residual is 0.789. Results reveal that our model can well depict the address utilization patterns over time.

As depicted in Fig. 7, the peak address utilization presents a growth with the increase of the lease time. This is because when the lease is set to a large value, address reclamation efficiency is reduced and more addresses are needed for the terminals. The results show that the model can reveal the relationship between address utilization and the lease time. In addition, we find that when the lease is smaller than 120 minutes, modeling results present the similar patterns with the emulation results. But when the lease is larger than 120 minutes, the model needs more IP addresses than emulation to satisfy the maximum online users. This is because more than 60% sessions are shorter than 120 minutes, more and more addresses assigned in the early stage are released and reclaimed by the DHCP server even when the lease becomes larger. These reclamation addresses can be reassigned to the terminals and slow the growing demand for addresses. The emulation technique better reflects the real requirements of the studied WLAN than the address utilization model, which assumes there are always enough addresses can be assigned to the terminals.

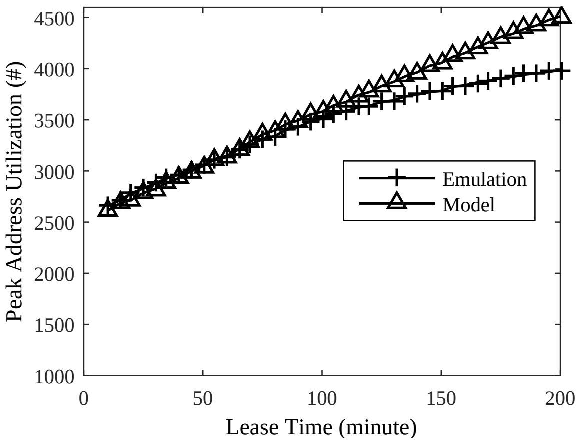


Fig. 7. Peak address utilization under different lease time settings.

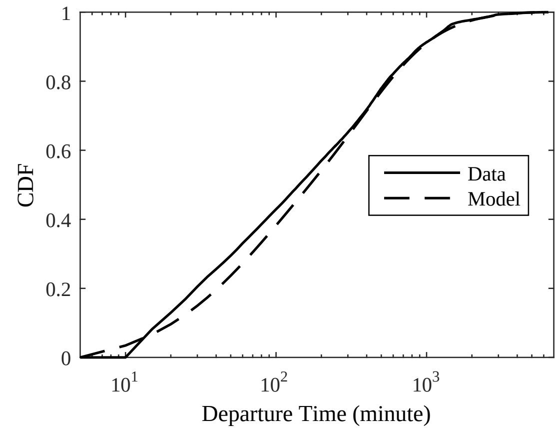


Fig. 8. Modeling results of departure time distribution.

VI. Relationship between DHCP load and the lease

To future reveal the relationship between DHCP load and the lease time, we then model the DHCP load according to user behaviors.

A. Departure Time Distribution

The departure time is calculated from a terminal leaving the WLAN to accessing it again. The terminals not coming back after leaving the WLAN are excluded. The departure time also follows the *three-stage hyper-exponential distribution* model. The density function of the departure time is shown as equation (16).

$$k'(x) = \mu_1 p_1 e^{-\mu_1 x} + \mu_2 p_2 e^{-\mu_2 x} + \mu_3 p_3 e^{-\mu_3 x} \tag{16}$$

$$k(x) = k'(x) \times \eta \tag{17}$$

The parameters of $k'(x)$ are determined with the same method to equation (1). When $c_1 = 294$ and $c_3 = 6$, the residual error is 0.018. The modeling results is shown in Fig. 8. Results show that our model can shed light on the departure time distribution. In equation (17), η is the proportion of the terminals that access the WLAN again after leaving it. And $k(x)$ is used to represent the departure time distribution of all terminals, i.e., including both the coming back and not coming back users after leaving the WLAN. Through statistics, the value of η is 0.89767 in our study.

B. Requesting New Address

In fact, most terminals omitting releasing the leases when they leave the WLAN. Some of these terminals may access the network again before the leases of the IP addresses expire. In this case, these terminals have no need of requesting new IP addresses. Otherwise, the terminals need to request new addresses. The probability of a terminal requesting a new IP address at time x is represented as equation (18).

$$\omega(x) = 1 - \frac{\sum_{t=1}^{x-1}\{\sum_{i=1}^{x-t}[\lambda(x-t-i)f(i)\bar{H}(t+i)]\cdot k(t)\}}{\lambda(x)} \tag{18}$$

In equation (18), $\bar{H}(x)$ is the CCDF of address usage time, $f(x)$ is the density function of session length, $\lambda(x)$ is the number of arrival terminals at time x, and $k(x)$ is the density function of departure time.

C. DHCP Load

DHCP load is generated under the following terminal behaviors, including accessing the network, extending the lease and leaving the network.

1) Accessing the network: As described in section IV, when a terminal accesses the network, if it needs to apply for a new IP address, the *discover* message, the *offer* message, the *request* message and the *acknowledge* message are generated. Otherwise, the address recently assigned to the terminal can still be used to access the network. In this case, the *request* message and the *acknowledge* message are generated. Equation (19) represents the number of DHCP messages generated by new arrival terminals at time x. Here, $\lambda(x)$ is the number of new arrival terminals at time x, and $\omega(x)$ is the probability of a terminal requesting a new IP address at time x.

$$N_1(x) = 4 \times \omega(x) \times \lambda(x) + 2 \times (1-\omega(x)) \times \lambda(x) \tag{19}$$

2) Extending the lease: When the remaining lease of an active terminal reaches to half of the lease, the terminal will request to extend the lease. This process will generate the *request* message and the *acknowledge* message. Equation (20) represents the number of DHCP messages generated when extending the lease at time x.

$$N_2(x, L_1, ..., L_N) = \sum_{d=1}^{N} N_2^d(x, L_d) \tag{20}$$

$$N_2^d(x, L_d) = 2 \times \sum_{i=1}^{x/\frac{L_d}{x}} \{\lambda_d(x - \frac{L_d}{2}\cdot i) \times [1 - F_d(\frac{L_d}{2} \times i)]\} \tag{21}$$

In equation (21), $F_d(x)$ is the CDF of the session length in area d, L_d is the lease time in area d, and $\lambda_d(x)$ is the number of new arrival terminals at time x in area d.

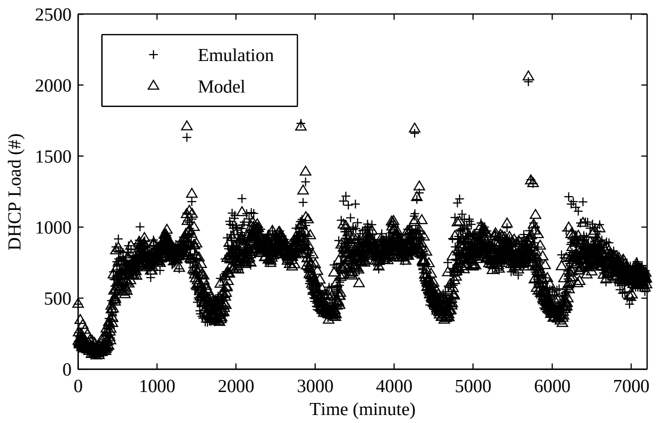


Fig. 9. Modeling and emulation results of DHCP load.

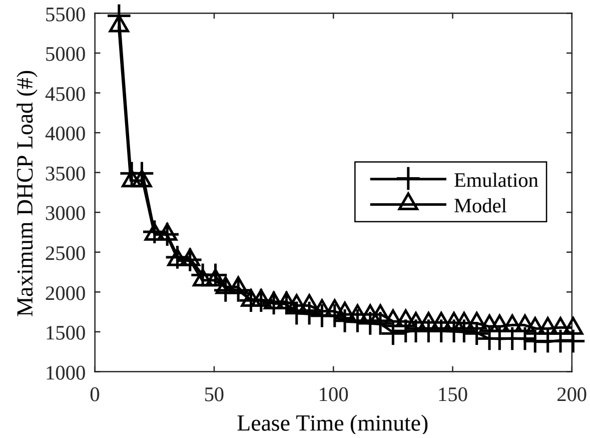


Fig. 10. Maximum DHCP load under different lease time settings.

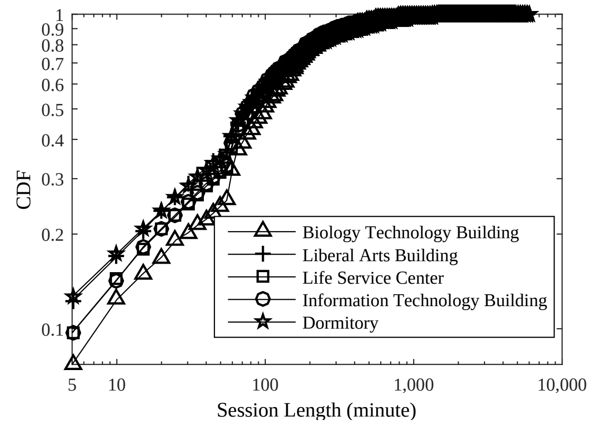


Fig. 11. Session length distribution across different areas.

3) Leaving the network: When a terminal leaves the network, it may send a *release* message to the DHCP server. Equation (22) represents the number of DHCP messages generated when leaving the network at time x. In equation (22), $f(x)$ is the density function of the session length, and β is the probability of a terminal releasing the lease actively.

$$N_3(x) = \beta \times \sum_{t=1}^{x} \lambda(x-t) f(t) \tag{22}$$

According to equation (19) $\sim$ equation (22), the number of DHCP messages at time x can be represented as equation (23).

$$N(x, L_1, ...L_N) = N_1(x) + N_2(x, L_1, ..., L_N) + N_3(x) \tag{23}$$

So far, we model the relationship between DHCP load and the lease. We then conduct a comparison evaluation under the default lease of 60 minutes. As shown in Fig. 9, the modeling results present similar patterns to the emulation results during the one week observation. Results reveal that our model can well depict the DHCP load patterns over time. This can be confirmed by calculating the SRE. More than 98% studentized residual values locate in the range of [-3, 3]. And the average absolute studentized residual is 0.85.

Fig. 10 shows the maximum DHCP load under different lease time settings. We find that the modeling results and the emulation results follow comparable patterns. With the increase of the lease time, the maximum DHCP load decreases quickly at the beginning and tends to be stable at the level of 1500. Large lease extends the address survival time and reduces the requirements of requesting new IP addresses or renewing the leases. As a result, the DHCP load decreases. However, setting the lease to 120 minutes can satisfy more than 60% terminals of the studied WLAN, so the maximum DHCP load gradually reaches to a stable state after that point. Results reveal that the models can express how DHCP leases affect the DHCP load.

VII. A Load-aware Lease Time Optimization Algorithm

According to the models of address utilization and DHCP load, we propose a load-aware optimization algorithm to determine proper leases for a WLAN with a given address space and terminal online patterns. In this study, we take the differences of the areas in session length distribution into account. For example, if an area of the WLAN has more short sessions, setting a short lease can improve the efficiency of address reclamation and provide more addresses for the burst of arrival terminals. Fig. 11 shows the session length distribution across the areas. Liberal Arts Building presents similar patterns with Dormitory. Nearly 56% sessions are shorter than 90 minutes, which indicates that a short lease time can satisfy a considerable proportion of terminals. Information Technology Building and Life Service Center have similar session length distributions. We can set the same lease for these two areas. 53% sessions of Biology Technology Building are longer than 90 minutes, which means it is better to set a larger lease for this area. The areas with the similar session length distribution are merged into the same group and will be set to the same lease. The merging makes the solution space decrease, which reduces the complexity of determining the lease time for different areas. The optimization objective and corresponding limitations are shown in equation (24). It means finding a combination of leases for different areas to minimize the DHCP load while control the address utilization under a

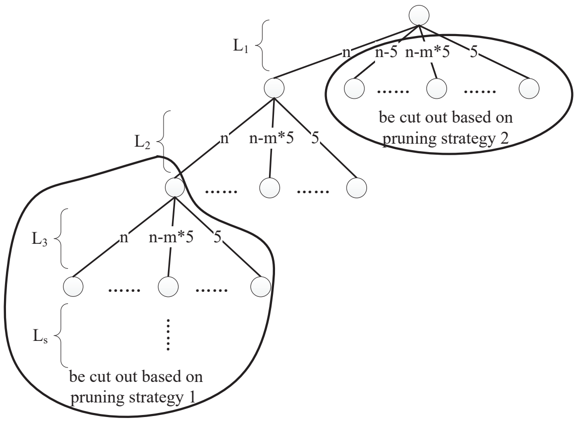


Fig. 12. The solution space of the leases for each area group.

threshold to satisfy the burst of online terminals.

$$\begin{aligned} &\min \max[N(x, L_1, ..., L_N)] \\ &s.t. \max[M(x, L_1, ..., L_N)] \leq Threshold \cdot Total_{IP} \end{aligned} \tag{24}$$

$N(x, L_1, ..., L_N)$ represents the DHCP load shown in equation (23) and $M(x, L_1, ..., L_N)$ represents the address utilization shown in equation (10). $Threshold$ refers to the proportion of IP addresses that can be assigned at the most and the remaining addresses are reserved for the burst of arrival terminals. $Total_{IP}$ refers to the number of available IP addresses of the WLAN. To get the optimal lease time combination, we first give two properties based on equation (10) and equation (23).

Property 1: When the lease of only one area is increased and the leases of other areas are not changed, the number of occupied IP addresses at time x will increase.

Property 2: When the lease of only one area is decreased and the leases of other areas are not changed, the DHCP load at time x will increase.

According to the above properties, we design two pruning strategies to optimize the search process of the solution space tree as shown in Fig. 12.

Pruning strategy 1: If the solution needs more addresses than the current optimal solution, the subtree whose root is the current node is cut out.

Pruning strategy 2: If the solution generates more DHCP load than the current optimal solution, the subtrees whose roots are the current node and its sibling nodes are cut out.

According to the above pruning strategies, we design a load-aware lease time optimization algorithm. ***Algorithm 3*** describes how to set the leases for each area of a WLAN. The WLAN has *p* areas and *q* available addresses. The areas are classified into *s* groups according to the characteristics of the session length distribution. The areas in the same group will share the same lease. The *threshold* represents the maximum proportion of the available addresses that can be assigned to the terminals. The *solution* represents the temporary lease time combination for the area groups. The *level* is the layer of the solution space tree. We denote *leaseTimeArray* the candidate lease time combination and *optimalSolution* the optimal lease time combination for the area groups.

In each level, we check each value of the *leaseTimeArray* from the largest one to the smallest one until one of the pruning strategies is satisfied (line 1-9). To apply the pruning strategies, we first construct two special solutions, which are marked by *minSolution* and *maxSolution* (line 3-4). The *minSolution* represents the smallest peak address utilization of the current temporary solution (line 7). The *maxSolution* represents the smallest DHCP load of the current temporary solution (line 8). If the peak address utilization of *minSolution* exceeds the threshold, *pruning strategy 1* is conducted (line 10-12). If the DHCP load of *maxSolution* exceeds the current optimal DHCP load, *pruning strategy 2* is conducted (line 13-15). Functions of *isOverIPThreshold* and *isOverOptimalDHCPLoad* are calculated based on equation (10) and equation (23) respectively. If the last lease time is determined, that is to say the pruning strategies are not conducted and the current solution is the optimal solution (line 16). Then the optimal DHCP load and the optimal solution are updated (line 17-18). In this case, there is no need to execute a deeper recursion call, because it has reached to the leaf node of the solution space tree (line 19). Otherwise, we conduct the depth-first search recursively of the solution space tree (line 21). If the search finishes, the current optimal solution is the final solution and the algorithm terminates (line 22).

Algorithm 3 Setting Leases for Each Area Group

```
Input: solution, level, threshold, leaseTimeArray
Initialization: solution ← new int [s], level ← 0
    leaseTimeArray ← {15, 30, 60, 90, 120, 180, 240, 360, 480 }
Function leaseSearch (solution, level, threshold, leaseTimeArray)
 1: for i = 0 to (length of leaseTimeArray) -1 do
 2:     solution[level] ← leaseTimeArray[i];
 3:     minSolution ← solution;
 4:     maxSolution ← solution;
 5:     j ← level + 1;
 6:     while  j < length of leaseTimeArray do
 7:         minSolution[j] ← min(leaseTimeArray);
 8:         maxSolution[j] ← max(leaseTimeArray);
 9:     end while
10:     if isOverIPThreshold (minSolution, threshold) then
11:         continue;
12:     end if
13:     if isOverOptimalDHCPLoad (maxSolution) then
14:         break;
15:     end if
16:     if  level = length of solution -1 then
17:         update the optimal DHCP load;
18:         optimialSolution ← solution;
19:         continue;
20:     end if
21:     leaseSearch (solution, level+1, threshold, leaseTimeArray)
22: end for
```

VIII. Evaluation on the Proposed Algorithm

The areas of the studied WLAN are divided into three groups, including {Liberal Arts Area, Dormitory}, {Information Technology Building, Life Service Center}, and {Biology Technology Building}. In our study, the optional values of the threshold are 100%, 95%, 90%, 85% and 80%. The optional values of the lease time are 15, 30, 60, 90, 120, 180, 240, 360, and 480. Given above, we run the algorithm to determine the leases for each area group of the WLAN. Fig. 13 shows the peak address utilization and maximum DHCP

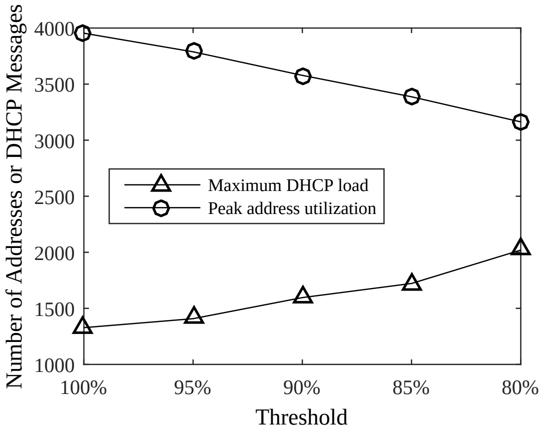


Fig. 13. Address utilization and DHCP load under each threshold.

load under different values of the threshold. Each threshold corresponds to an optimal combination of leases shown in Table II. We can see that the maximum DHCP load increases, while the peak address utilization decreases with the decrease of the threshold. As statistics and discussion with the operators of the studied WLAN, we know that it is better to reserve 10% address space for the burst of online terminals. In this case, the optimal lease combination for the three area groups is {15, 120, 120}. Under this lease time settings, the peak address utilization is 3578 and the maximum DHCP load is 1596. Compared with the default lease time of 60 minutes for all areas, the peak DHCP load is reduced by 21.7% and the peak address utilization is increased by 13.2%, but we can make sure that there are always 10% available addresses for the burst of arrival terminals.

We also evaluate the recommended lease combination of {15, 120, 120} in a whole day. As depicted in Fig. 14, Compared with the default lease of 60 minutes, the DHCP load is reduced by 36.85% on average and the address utilization is increased by 12.88% on average. Compared with the lease of 120 minutes suggested by the emulation technique, the addresses utilization is reduced by 4.72% on average and the DHCP load is increased by 2.65% on average. Evaluation results show that the proposed models and optimization algorithm can determine a proper lease time combination for the WLAN at the area granularity. Using this area-grained method, we can minimize the DHCP load and at the same time make a reservation of address for the burst of arrival smart terminals. This could reduce the possibility that a terminal in a scarce address pool cannot get an address. In addition, it is flexible to adjust the proportion of the reserved address space and determine the leases to meet the dynamics of smart terminals.

Our method is applicable to any WLAN with scarce IP addresses if related data can be provided. The algorithm is executed periodically after the network has been deployed. The WLAN operator is responsible for gathering the traces and implementing the algorithm. Therefore, it does not need to make any changes to the DHCP specifications.

TABLE II
THE LEASE TIME COMBINATION OF EACH THRESHOLD

Threshold	Lease Time Combination
100%	(15, 120, 240)
95%	(15, 120, 180)
90%	(15, 120, 120)
85%	(15, 120, 90)
80%	(15, 120, 60)

IX. CONCLUSION AND FUTURE REMARKS

In this paper, we study how DHCP leases can be made to meet smart terminals with transient access patterns. Our goal is taking full use of the address resource under the following restrictions: reducing the DHCP load as much as possible; controlling the address utilization under a threshold. The former decreases the load on the DHCP server and the terminals, while the latter copes with the burst of online users. We first propose an emulation technique to evaluate address utilization and DHCP load under different lease time settings. Then we model the relationship between address utilization and the lease time, as well as the relationship between DHCP load and the lease time. At last, we propose a load-aware lease time optimization algorithm to determine the leases for different areas. The proposed emulation technique provides experimental basis for setting the lease for the whole WLAN, while the proposed models and optimization algorithm help to set the leases for each area of the WLAN based on theoretical analysis. Evaluation results have proved the effectiveness of the emulation technique, models and optimization algorithm proposed in this paper.

In addition to setting static leases, we will improve our methods to adjust the leases dynamically, which can cope with the user behaviors changing over time.

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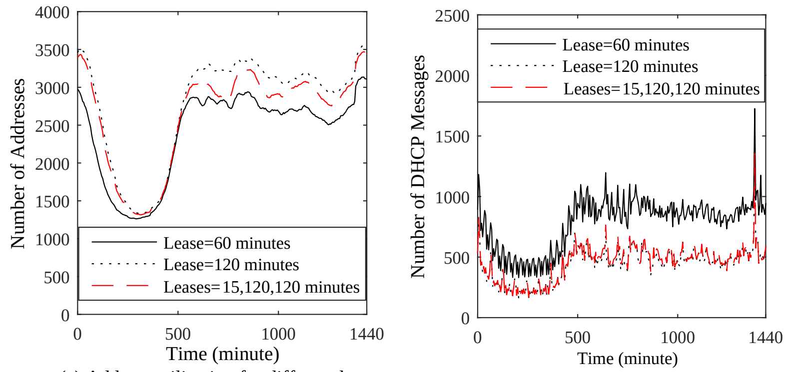
REFERENCES

[1] R. Droms , "Dynamic Host Configuration Protocol", RFC 2131 (Draft Standard), Internet Engineering Task Force, 1997.
[2] IPv4 address exhaustion. https://en.wikipedia.org/wiki/IPv4 address shortage.
[3] I. Papapanagiotou, E. M. Nahum, and V. Pappas, Configuring DHCP leases in the smartphone era, in *Proceedings of the 2012 ACM conference on Internet measurement conference*, 2012: 365-370.
[4] M. Khadilkar, N. Feamster, M. Sanders, and R. Clark, Usage-based DHCP lease time optimization, in *Proceedings of the 7th ACM SIGCOMM conference on Internet measurement*, 2007: 71-76.



(a) Address utilization for different leases

(b) DHCP load for different leases

Fig. 14. Address utilization and DHCP load under different lease time settings.

[5] C. Tuduce and T. Gross, A Mobility Model Based on WLAN Traces and its Validation, in *Proceedings of IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, 2005: 664-674.

[6] W. J. Hsu, T. Spyropoulos , K. Psounis and A. Helmy , "Modeling spatial and temporal dependencies of user mobility in wireless mobile networks," *IEEE/ACM Transactions on Networking (ToN)*, 17(5), 2009: 1564 -1577.

[7] H. Falaki, D. Lymberopoulos, R. Mahajan S. Kandula, and D. Estrin, "A First Look at Traffic on Smartphones," in *Proceedings of the 10th ACM SIGCOMM conference on Internet measurement*, 2010: 281-287.

[8] H.Falaki, R.Mahajan, S. Kandula D.Lymberopoulos R.Govindan, and D.Estrin, "Diversity in Smartphone Usage," in *Proceedings of the 8th international conference on Mobile systems, applications, and services*, 2010: 179-194.

[9] A. Gember, A. Anand, and A. Akella, A comparative study of handheld and non-handheld traffic in campus Wi-Fi networks, in *Proceedings of the 12th international conference on Passive and active measurement (PAM)*, 2011: 173-183.

[10] J. Kim and A. Helmy, "The evolution of wlan user mobility and its effect on prediction," in *Proceedings of the 7th International Wireless Communications and Mobile Computing Conference*, 2011: 226-231.

[11] X. Chen, R. Jin, K. Suh, B. Wang, and W. Wei, Network performance of smart mobile handhelds in a university campus WiFi network, in *Proceedings of the 2012 ACM conference on Internet measurement conference*, 2012: 315-328.

[12] W. J. Hsu, D. Dutta, and A. Helmy, Structural Analysis of User Association Patterns in University Campus Wireless LANs, *IEEE Transactions on Mobile Computing*, 11(11), 2012: 1734-1748.

[13] X. Chen, L. Lipsky, K. Suh, B. Wang, and W. Wei, Session lengths and ip address usage of smartphones in a university campus wifi network: Characterization and analytical models, in *Proceedings of the 2013 IEEE 32nd International Performance Computing and Communications Conference*, 2013:1-9.

[14] U. Kumar, J. Kim, and A. Helmy, Changing patterns of mobile network (WLAN) usage: smart-phones vs. laptops, in *Proceedings of the 9th International Wireless Communications and Mobile Computing Conference*, 2013: 1584-1589.

[15] S. C. Geyik, E. Bulut, and B. K. Szymanski, Grammatical inference for modeling mobility patterns in networks, *IEEE Transactions on Mobile Computing*, 12(11), 2013: 2119-2131.

[16] T. Wang, W. Jia, G. Xing, and M. Li, Exploiting statistical mobility models for efficient Wi-Fi deployment, *IEEE Transactions on Vehicular Technology*, 62 (1), 2013: 360-373.

[17] N. Cruz, H. Miranda, and P. Ribeiro, The evolution of user mobility on the eduroam network, in *IEEE International Conference on Pervasive Computing and Communications Workshops*, 2014: 249-253.

[18] A. K. Das, P. H. Pathak, C. N. Chuah, P. Mohapatra, "Characterization of wireless multi-device users," In *Proceedings of the 12th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, 2015: 327-335.

[19] V. Brik, J. Stroik, and S. Banerjee, "Debugging dhcp performance," in *Proceedings of the 4th ACM SIGCOMM conference on Internet measurement*, 2004: 257-262.

[20] T. V. Do, An efficient solution to a retrial queue for the performability evaluation of DHCP, *Computers & Operations Research*, 37(7), 2010: 1191-1198.

[21] S. Seneviratne, A. Seneviratne, P. Mohapatra, and P. U. Tournoux, Characterizing WiFi connection and its impact on mobile users: practical insights, in *Proceedings of the 8th ACM international workshop on Wireless network testbeds, experimental evaluation & characterization*, 2013: 81-88.

[22] L. Vu, D. Turaga, S. Parthasarathy, Impact of DHCP churn on network characterization, *ACM SIGMETRICS Performance Evaluation Review*, 2014: 587-588.

[23] G. C. Moreira Moura, C. H. G. Ganan, Q. B. Lone, P. Poursaied, H. Asghari, and M. J. G. Van Eeten, How Dynamic is the ISPs Address Space? Towards Internet-Wide DHCP Churn Estimation, in *IFIP Networking Conference (IFIP Networking)*, 2015: 1-9.

[24] X. Wei, N. C. Valler, H. V. Madhyastha, I. Neamtiu, M. Faloutsos, "A behavior-aware profiling of handheld devices," in *Proceedings of the 2015 IEEE Conference on Computer Communications (INFOCOM)*, 2015, pp. 846-854.

[25] Android Rapidly Repeats DHCP Transactions Many Times, October 2013. https://code.google.com/p/android/issues/detail?id=33590.

[26] A. Feldmann and W. Whitt, Fitting Mixtures of Exponentials to Long-Tail Distributions to Analyze Network Performance Models, in *Proceedings of the Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Driving the Information Revolution (INFOCOM)*, 1997: 1096-1104.

[27] A. K. Das, P. H. Pathak, C. N. Chuah, P. Mohapatra, "Characterization of wireless multidevice users," *ACM Transactions on Internet Technology (TOIT)*, 2016, 16(4): 29.

[28] X. Wei, N. C. Valler, H. V. Madhyastha, I. Neamtiu, M. Faloutsos, "Characterizing the behavior of handheld devices and its implications," *Computer Networks*, 2017, 114(2017): 1-12.

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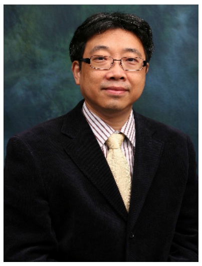

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