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A State Transition-Aware Energy-Saving Mechanism for Dense WLANs in Buildings

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ABSTRACT With the explosive growth of smart terminals, access points (APs) are densely deployed in the buildings of enterprise, campus, hotel, and so on, to provide sufficient coverage and capacity for peak user demands. However, existing studies show that during the off-peak periods, not all the capacity is needed and a large fraction of low-utilization or idle APs cause a great deal of energy waste in these buildings. Although many solutions have been proposed to switch on/off the APs according to the user needs, few works consider the energy cost by state transition. In this paper, we propose a state transition-aware energy-saving mechanism for dense wireless local area networks, which can dynamically switch the APs' states to meet the user needs while controlling the switching frequency and balancing the number of associated users of each AP. First of all, we analyze the most recent user behaviors, which are used to design the energy-saving mechanism. Then, we model the proposed mechanism in order to set relevant parameters reasonably. Finally, evaluation results show that comparing with a typical static strategy, the energy consumption is reduced by 24.3%, and the average available bandwidth is increased by 27.8%. Meanwhile, the switching frequency is reduced by 14.3% as well.

INDEX TERMS Mobile computing, energy management, state transition, dense WLANs, buildings.

I. INTRODUCTION

To meet the needs of mobile terminals in the peak demand hours, dense APs are deployed in the buildings of enterprise, campus and hotel, etc., to provide sufficient coverage and capacity. However, peak user demands rarely occur [1]. During the off-peak periods, a large fraction of low-utilization or idle APs result in energy waste of the buildings.

The energy consumption of APs presents differences when they run in different states. To achieve the objective of energy saving, existing studies have tried to reduce such kind of wastage by dynamically switching on/off APs according to the real-time user needs [2], [3], or by static configuration and switching on/off scheduling according to the historical traces [4]. The essence of these methods can be concluded that the low-utilization or idle APs are switched off to reduce the energy consumption, while the closed APs are switched on to meet the demands of the increasing active users. However, state transition introduces extra energy cost, and frequently opening and closing an AP will affect the performance of the associated users, as well as shorten the service life of the AP. Therefore, in addition to saving energy by providing resource on demands, we should also control the switching frequency as low as possible. As a supplement to previous studies, we take the energy consumption caused by state transition into account when designing the energy-saving mechanism for dense WLANs, which can further reduce the energy consumption in buildings while guaranteeing the available bandwidth and controlling the switching frequency. The main contributions of this study are summarized as follows.

(1) We analyze some most recent user behaviors according to the up-to-date traces. We find that the user arrival rate follows the Poisson distribution with a parameter of 0.75, and the session length distribution follows the Exponential

distribution with a parameter of 0.019. Analysis results reflect the current user demands of capacity and provide a basis for the follow-up mechanism design.

(2) We propose a state transition-aware energy-saving mechanism for dense WLANs in buildings. To best of our knowledge, we take the energy consumed by state transition into account for the first time. In addition, the queuing theory is used to model the proposed energy-saving mechanism in order to set the experimental parameters reasonably.

(3) We evaluate the proposed energy-saving mechanism through a numerical analysis and an experimental analysis. Numerical analysis determines the parameters for the experiments, and experimental results show that comparing with a typical strategy,the energy consumption is reduced by 24.3% and the available bandwidth per user is increased by 27.8%. Meanwhile the switching frequency is reduced by 14.3% as well.

This paper conducts a case study on greening the dense WLANs in buildings based on the data gathered from a teaching building of a campus WLAN. However, both the mechanism and the models are applicable to any WLAN if related data can be provided. That is to say, our work can be used to any WLAN adopting centralized access controllers to manage the dense APs.

The remainder of this paper is organized as follows. Related work is presented in Section II. The up-to-date user behaviors are analyzed in Section III. The transition-aware energy-saving mechanism for dense WLANs is described in Section IV. We model the proposed mechanism in Section V. Section VI determines the experimental parameters and evaluates the effectiveness of the proposed mechanism. Section VII concludes the whole paper.

II. RELATED WORK

The dense APs deployed in the WLANs cause the problem of energy waste. In order to reduce such kind of wastage, many solutions are proposed to achieve energy-efficient WLANs. Jardosh *et al.* [1] firstly proposed the resource-on-demand strategy for dense WLANs. APs in the WLAN are clustered based on their Euclidean distance and one AP is chosen as the head for each cluster. The APs are powered on/off according to the number of users or user traffic in each cluster. Similar thought but different clustering methods and user demand estimation metrics are used in [2] and [3]. Marsan *et al.* [4] presented a analytical model of switching on/off strategies of APs in dense WLANs. Policies of association-based and traffic-based are proposed to turn on/off the APs in the same cluster. Debele *et al.* [5] implemented these two strategies in part of a campus WLAN to evaluate the practical effectiveness in energy savings. Da Silva *et al.* [6] investigated the energy-performance trade-off in dense WLANs through a queuing study. They presented a set of algorithms to make the capacity adaptive to the number of associated users in order to increase the amount of saved energy. Similarly, Marsan and Meo [7] presented simple queuing models to assess the effectiveness of the AP sleep modes in dense WLANs. Ganji *et al.* [8] extracted energy-relevant usage and user mobility patterns, and then evaluated potential energy-savings and performance of on/off switching strategies. Debele *et al.* [9] proposed a model to describe resource-on-demand strategies and used the model to study AP active and inactive periods, switching frequency and energy savings. Chen *et al.* [10] proposed a QoS-aware AP energy saving mechanism based on SDN (Software-Defined Networking [11]). Xu *et al.* [12] presented an AP sleeping and user offloading scheme to reduce energy consumption. Many studies have tried reduce energy consumption by adjusting the APs in different running states (i.e., on/off) according to the user demands. However, few studies consider the energy consumption during the state transition. Different from previous studies, we take the energy consumed by state transition into account when designing the energy-saving mechanism, which can further reduce the energy consumption while controlling the switching frequency and guaranteeing the user available bandwidth.

III. UNDERSTANDING USER BEHAVIOURS

With the explosive increase of mobile terminals, there are many studies understanding mobile user behaviors [13]–[17]. In this paper, we also analyze some user behaviors based on the up-to-date traces, including online user number, user arrival rate and session length distribution. Different from previous studies, we use these most recent user behaviors to design energy-efficient algorithms for the studied WLAN through a centralized control manner, which is different from some existing studies using the distributed methods.

The traces are collected from a teaching building of a campus WLAN. This building contains 100 APs, which are distributed in 50 classrooms. The APs are controlled by one Access Controller (*AC*). We collected the logs of the *AC* from March 13th (Monday) 2017 to March 17th (Friday) 2017 through *SNMP* at the scale of every five minutes. 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 the *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 the *AC* logs to estimate the user behaviors of one classroom.

A. USER ONLINE NUMBER

As depicted in Fig. 1, the online users present great changes over time. The maximum is 30, while the minimum is 0. This room contains one AP with two groups of antennas. During the peak periods, all the groups of antennas need to be switched on to provide sufficient capacity. However, during the off-peak periods, not all the capacity is needed, and we could switch off a group of antenna or the whole AP, which can save the energy consumption.

TABLE 1. Symbols used in the proposed transition-aware energy-saving mechanism.

Symbols	Meaning	Units
Pwr_i, $i \in \{0,1,2\}$	power consumption under the fully closed, energy-saving and fully opened states	W
$Pwr_{0,1}$	energy consumption from the fully closed state to the energy-saving state	J
$Pwr_{1,2}$	energy consumption from the energy-saving state to the fully opened state	J
Cap_i, $i \in \{0,1,2\}$	association capacity under the fully closed, energy-saving and fully opened states	$\#$
Bwd_i, $i \in \{0,1,2\}$	available bandwidth under the fully closed, energy-saving and fully opened states	$Mbps$

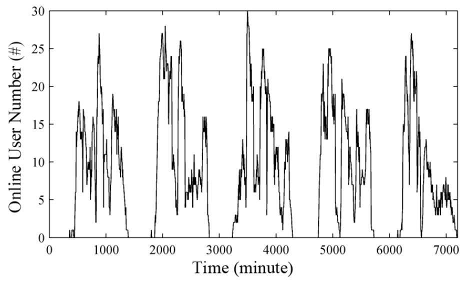

FIGURE 1. The number of online users.

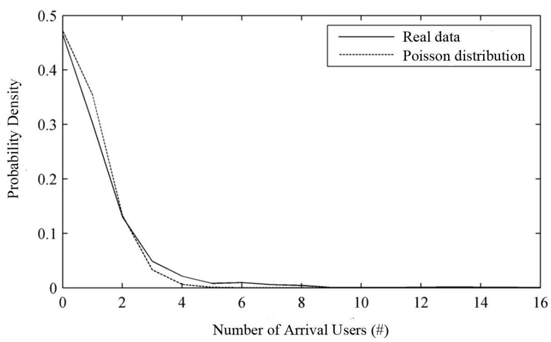

FIGURE 2. The user arrival rate distribution.

B. USER ARRIVAL RATE

As statistics, the number of arrival users concentrates in 0, 1 and 2 at each observation point. During the period of 6:00 - 23:00, the number of arrival users presents similar patterns. We use the *Maximum Likelihood Estimation* of Poisson distribution to model the user arrivals. As shown in Fig. 2, the user arrival rate can be fitted well with the Poisson distribution model with a parameter of 0.75.

C. SESSION LENGTH DISTRIBUTION

As statistics, nearly 40% sessions are shorter than 30 minutes, and more than 60% sessions are shorter than 100 minutes. We use the *Maximum Likelihood Estimation* of Exponential distribution to model the session length distribution. As shown in Fig. 3, the session length can be fitted well with the Exponential distribution with a parameter of 0.019.

IV. A STATE TRANSITION-AWARE ENERGY-SAVING MECHANISM

The APs in our study are enabled with $2 \times 2MIMO$, i.e., two groups of transmit and receive antennas. An AP will be running at one of the following three states, including (1) fully opened state: all antennas are switched on; (2) energy-saving state: a group of antenna is switched on and the other is switched off; (3) fully closed state: all the antennas are switched off.

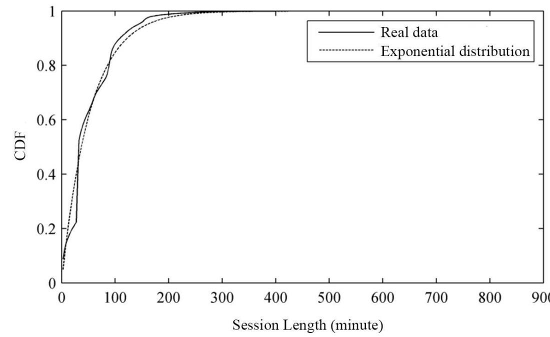

FIGURE 3. The user session length distribution.

In this study, we not only consider the energy consumption of the APs running at different states, but also consider the energy consumption caused by state transition from the closed state to the energy-saving state, and from the energy-saving state to the fully opened state. To distinguish the energy consumption of the APs running at different states, we assume that the APs cannot be switched from the fully closed state to the fully opened state. To at most minimize the influence on user performance, we assume that state transition from the fully opened state to the fully closed state is also not allowed. Table I shows some symbols that will be used in the description of the proposed mechanism.

A. MANAGEMENT MECHANISM FOR USER ASSOCIATION

When a user arrives, the user will associate with an AP. Taking the energy consumption caused by state transition into account, the user association follows the following three principles.

(1) Among the APs which cover the arrival user, the user chooses to associate with the AP without causing state transition. If there are many APs can be chosen, the user chooses to associate with the AP with the minimum online users.

(2) If all the APs in the coverage need state transition, the user chooses to associate with an AP running at the energy-saving state. If there are more than one AP running at the energy-saving states, the user chooses to associate with the nearest AP (estimated by *Received Signal Strength Indicator* (*RSSI*)) from it. The chosen AP is switched from the energy-saving state to the fully opened state.

(3) If there is no AP running at the energy-saving state, the user chooses to associate with the nearest AP in the

coverage and running at the fully closed states. The chosen AP is switched from the fully closed state to the energy-saving state.

Algorithm 1 Management Mechanism for User Association

Require: *apCandidateList*
Ensure: *apAssociated*
Function *getAPtoAssociate* (*apCandidateList*)
1: $notransitionAPList \leftarrow \phi$, $greenstateAPList \leftarrow \phi$, $offstateAPList \leftarrow \phi$;
2: **for** each candidate AP ap_i in *apCandidateList* **do**
3:   **if** $ap_i.userNum < Cap_{ap_i.state}$ **then**
4:     $notransitionAPList.add(ap_i)$;
5:   **else if** $ap_i.userNum = Cap_{ap_i.state}$ and $ap_i.state = 1$ **then**
6:     $greenstateAPList.add(ap_i)$;
7:   **else if** $ap_i.userNum = Cap_{ap_i.state}$ and $ap_i.state = 0$ **then**
8:     $offstateAPList.add(ap_i)$;
9:   **end if**
10: **end for**
11: **if** $notransitionAPList.size > 0$ **then**
12:   **return** *getMinUserNumberAP*(*notransitionAPList*)
13: **else if** $greenstateAPList.size > 0$ **then**
14:   **return** *getMinDistanceAP*(*greenstateAPList*)
15: **else if** $offstateAPList.size > 0$ **then**
16:   **return** *getMinDistanceAP*(*offstateAPList*)
17: **else**
18:   **return** *NULL*
19: **end if**

Algorithm 1 describes how an arrival user choose to associate with an AP. We denote *apCandidateList* the AP list covering the arrival user. We first classify the AP list into three groups, including the *notransitionAPList* referring to the APs allowing the arrival user to associate with without state transition, the *greenstateAPList* referring to the APs which are in the energy-saving states and have reached to the upper limit of user association, and the *offstateAPList* referring to the APs which are in the fully closed states. If three are APs in the list of *notransitionAPList*, the arrival user chooses to associate with the AP with the fewest users (line 11-12). Note that if there are two APs with the same number of users, the AP nearest from the user will be chosen (line 12). Otherwise, if there are APs in the list of *greenstateAPList*, the arrival user chooses to associate with the AP nearest from the user (line 13-14). We should open another group of antenna to serve the arrival user, i.e., the AP needs to be switched from the energy-saving state to the fully opened state. If there are no APs running at the energy-saving states, the AP nearest from the user will be chosen to be switched from the fully closed state to the energy-saving state (line 15-16). At last, if the arrival user does not belong to any one of the three conditions, it cannot associate with any one of the APs (line 17-18).

B. MANAGEMENT MECHANISM FOR AP STATE TRANSITION

To achieve the goal of energy saving, APs are switched on and off by the centralized controller according to the user needs.

AP state transition is triggered by user arrival and departure. When a user arrives, state transition is necessary in some cases according to the management mechanism for user association described in Section IV. A. Switching frequency will not be controlled in order to guarantee the success of user association. ***Algorithm 2*** describes how to manage the state transition for user arrival. The associated AP may be switched from the fully closed state to the energy-saving state and the number of users is changed from 0 to 1 (line 1-3). The associated AP may also be switched from the energy-saving state to the fully opened state and the number of users is increased by one (line 4-6). Otherwise, no state transition happens, but the number of users of the associated AP is increased by one (line 7-8).

Algorithm 2 State Transition for User Arrival

Require: *associatedAP*
Function *arrival* (*associatedAP*)
1: **if** $associatedAP.state = 0$ **then**
2:   $associatedAP.state \leftarrow 1$;
3:   $associatedAP.num \leftarrow 1$;
4: **else if** $associatedAP.state = 1$ and $associatedAP.num = Cap_1$ **then**
5:   $associatedAP.state \leftarrow 2$;
6:   $associatedAP.num \leftarrow associatedAP.num+1$;
7: **else**
8:   $associatedAP.num \leftarrow associatedAP.num+1$;
9: **end if**

For user departure, we introduce two hysteresis coefficients of h_0 and h_1 to control the switching frequency.

1) *Hysteresis coefficient* h_0: There is an AP which is running at the energy-saving state. When the associated users of this AP decrease to 0, and the APs in the overlapping coverage area carry fewer than h_0 users, the AP is switched from the energy-saving state to the fully closed state.

2) *Hysteresis coefficient* h_1: There is an AP which is running at the fully opened state. When the number of associated users of this AP is changed from $Cap_1 - h_1$ to $Cap_1 - h_1 - 1$, the AP is switched from the fully opened state to the energy-saving state.

Algorithm 3 describes how to manage the state transition for user departure. When a user leaves, the associated AP may be switched from the energy-saving state to the fully closed state and the number of users is changed from 1 to 0 (line 1-3). The associated AP may also be switched from the fully opened state to the energy-saving state, and the number of users is reduced by one (line 4-6). Otherwise, no state transition happens, but the number of users of the associated AP is reduced by one (line 7-8).

Algorithm 3 State Transition for User Departure

Require: *associatedAP*
Function *Departure* (*associatedAP*)
if $associatedAP.state = 1$ and $associatedAP.num = 1$ and $associatedAP.overlapAP.num < h_0$ **then**
  $associatedAP.state \leftarrow 0$;
  $associatedAP.num \leftarrow 0$;
else if $associatedAP.state = 2$ and $associatedAP.num = Cap_1 - h_1$ **then**
  $associatedAP.state \leftarrow 1$;
  $associatedAP.num \leftarrow associatedAP.num\text{-}1$;
else
  $associatedAP.num \leftarrow associatedAP.num\text{-}1$;
end if

V. MODELING THE PROPOSED MECHANISM

In this section, we conduct a theoretical analysis on the proposed energy-saving mechanism based on queuing theory. Each AP is modeled as a M/M/N queuing system. Then the association rate, the energy-saving efficiency and the hysteresis coefficients are analyzed.

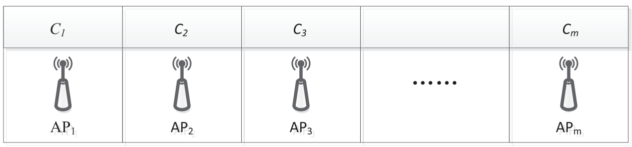

FIGURE 4. A scenario of dense WLAN.

A. MODEL DESCRIPTION

As depicted in Fig. 4, there are m classrooms and each classroom has one AP. Each AP can provide coverage for the room that the AP locates in, as well as its neighbour rooms. For example, AP_1 covers both C_1 and C_2, and AP_2 covers C_1, C_2 and C_3. The scenario shown in Fig. 4 can be expressed by expression (1). S_i represents the state of AP_i and the values of S_i could be 0 (fully closed), 1 (energy-saving) and 2 (fully opened). R_i represents the number of users that associated with AP_i.

$$(S_1, S_2, \ldots, S_m, R_1, R_2, \ldots, R_m) \tag{1}$$

In order to guarantee the completed coverage, two adjacent APs cannot be running at the fully closed states at the same time. That is to say when we use $(S_1, S_2, \ldots, S_m)$ to describe the APs' states, the sequence values like (1, 2, 0, 0, 1, ...) will not appear. In addition, S_m and R_m should meet the following rules.

$$if\ S_i = 0, \quad then\ R_i = 0 \tag{2}$$
$$if\ S_i = 1, \quad then\ 0 \le R_i \le Cap_1 \tag{3}$$
$$if\ S_i = 2, \quad then\ Cap_1 - h_1 \le R_i \le Cap_2 \tag{4}$$

Assuming there are 4 classrooms and each AP can be associated with at most 30 users, i.e., $(S_1, S_2, S_3, S_4, R_1, R_2, R_3, R_4)$, the state space is $3^4 * 30^4$. The state space will be extremely large when the number of APs is large. To reduce the state space, $M/M/n$ is used to model each AP as a queuing system. $M/M/n$ means the user arrival rate follows the Poisson process, the service time follows the Exponential distribution, and the AP can provide services for n users at the same time. As analysis in Section III, the user arrival rate follows the Poisson process, and the online session length follows the Exponential distribution. Therefore, it is reasonable to model each AP as a queuing system of $M/M/Cap_2$. Cap_2 is the maximum number of users that a fully opened AP can be associated with.

B. ASSOCIATION RATE

For the i_{th} classroom, we denote λ_i the average arrival rate and $1/\mu_i$ the average online session length of the users. The average user association rate of AP_i is A_i. According to the user association mechanism described in Section IV. A, λ_i and A_i may not be equal to each other, because a user arriving at the classroom C_i may not associate with AP_i deployed in C_i. For example, the user may associate with AP_{i-1} or AP_{i+1}, which are deployed in the neighbour classrooms of AP_i. The relationship between λ_i and A_i is expressed by equation (5).

$$A_i = \begin{cases} b_i\lambda_i + c_i\lambda_{i+1} & i = 1 \\ a_i\lambda_{i-1} + b_i\lambda_i + c_i\lambda_{i+1} & 1 < i < m \\ a_i\lambda_{i-1} + b_i\lambda_i & i = m \end{cases} \tag{5}$$

Where a_i, b_i and c_i are the real numbers locating in the closed interval of [0, 1]. According to the additivity property of Poisson process, the average user association rate also follows the Poisson process.

We denote $\pi^i_{n,s}$ the steady-state probability of AP_i deployed in C_i with s state and n associated users, where n is an integer and $n \in [0, Cap_2]$, $s \in \{0, 1, 2\}$. We denote π^i_n the steady-state probability of AP_i with n associated users. Since AP_i can be modeled as a queuing system of $M/M/Cap_2$, π^i_n can be expressed by equation (6).

$$\pi^i_n = \frac{1}{n!}(A_i/\mu_i)^n e^{-A_i/\mu_i} \tag{6}$$

According to the management mechanisms of user association and state transition, we build the relationship between $\pi^i_{n,s}$ and π^i_n. Equation (7) $\sim$ equation (9) show the steady-state probabilities of AP_1, AP_m and AP_i running at the fully closed states with n associated users.

$$\pi^1_{n,0} = \pi^1_{0,0} = \pi^1_0 - \pi^1_{0,1} = \pi^1_0 - \mu_1\pi^1_1\left(1 - \sum_{n=0}^{h_0}\pi^2_n\right) \tag{7}$$

$$\pi^m_{n,0} = \pi^m_{0,0} = \pi^m_0 - \pi^m_{0,1} = \pi^m_0 - \mu_1\pi^m_1\left(1 - \sum_{n=0}^{h_0}\pi^{m-1}_n\right) \tag{8}$$

$$\begin{aligned}\pi^i_{n,0} &= \pi^i_{0,0} = \pi^i_0 - \pi^i_{0,1} \\ &= \pi^i_0 - \mu_1\pi^i_1\left(1 - \sum_{n=0}^{h_0}\left(\pi^{i-1}_n\sum_{l=0}^{h_0-n}\pi^{i+1}_l\right)\right) \\ &\qquad i \subseteq [2, m-1]\end{aligned} \tag{9}$$

$$\begin{aligned}\pi^i_{n,1} &= \pi^i_{0,1} + \sum_{n=1}^{Cap_1-h_1} \pi^i_{n,1} + \sum_{n=Cap_1-h_1+1}^{Cap_1} \pi^i_{n,1} \\ &= \pi^i_{0,1} + \sum_{n=1}^{n=Cap_1-h_1} \pi^i_n + \frac{\pi^i_{Cap_1-h_1}\cdot A_i}{\pi^i_{Cap_1-h_1}\cdot A_i + \pi^i_{Cap_1+1}\cdot (Cap_1+1)\cdot \mu_i} \sum_{n=Cap_1-h_1+1}^{Cap_1} \pi^i_n \end{aligned} \quad (10)$$

$$\begin{aligned}\pi^i_{n,2} &= \sum_{n=Cap_1-h_1+1}^{Cap_1} \pi^i_{n,2} + \sum_{n=Cap_1+1}^{Cap_2} \pi^i_{n,2} \\ &= \frac{\pi^i_{Cap_1+1}\cdot (Cap_1+1)\cdot \mu_i}{\pi^i_{Cap_1-h_1}\cdot A_i + \pi^i_{Cap_1+1}\cdot (Cap_1+1)\cdot \mu_i} \sum_{n=Cap_1-h_1+1}^{Cap_1} \pi^i_n + \sum_{n=Cap_1+1}^{Cap_2} \pi^i_{n,2} \end{aligned} \quad (11)$$

Equation (10), as shown at the top of this page, shows the steady-state probability of AP_i running at the energy-saving state with n associated users. It is the sum of the probabilities of $n = 0$, $n \subseteq [1, Cap_1 - h_1]$ and $n \subseteq [Cap_1 - h_1 + 1, Cap_1]$. As shown in equation (11), as shown at the top of this page, the steady-state probability of AP_i running at the fully opened state with n associated users is the sum of the probabilities of $n \subseteq [Cap_1 - h_1 + 1, Cap_1]$ and $n \subseteq [Cap_1 + 1, Cap_2]$.

We then express the steady-state probabilities of each AP running at different states. Equation (12) is the steady-state probability of AP_1 running at the fully closed state. The value is equal to $\pi^1_{n,0}$ because the number of associated users is 0 when AP_1 is switched off. Similarly, the steady-state probability of AP_m is equal to $\pi^m_{n,0}$ when it is switched off. Equation (14) is the steady-state probability of AP_i running at the fully closed state. The value is equal to $\pi^i_{n,0}$. Equation (15) and equation (16) are the steady-state probabilities of AP_i running at the energy-saving state and the fully opened state respectively. The probability calculation considers all the possible numbers of users associated with AP_i.

$$P(S_1 = 0) = \pi^1_{n,0} \quad (12)$$

$$P(S_m = 0) = \pi^m_{n,0} \quad (13)$$

$$P(S_i = 0) = \pi^i_{n,0}, \quad i \subseteq [2, m-1] \quad (14)$$

$$P(S_i = 1) = \sum_{n=0}^{Cap_1} \pi^i_{n,1} \quad (15)$$

$$P(S_i = 2) = \sum_{n=0}^{Cap_2} \pi^i_{n,2} \quad (16)$$

$$\begin{aligned} a_2 = {} & P((S_1 = 0) \cap (S_2 = 1)) \\ & + P((S_1 = 0) \cap (S_2 = 2) \cap (R_2 < Cap_2)) \\ & + P((S_1 = 1) \cap (S_2 = 1) \cap (R_2 < R_1)) \\ & + P((S_1 = 1) \cap (S_2 = 2) \cap (R_2 < Cap_2) \\ & \cap (R_1 = Cap_1)) + P((S_1 = 1) \cap (S_2 = 2) \\ & \cap (R_2 < Cap_2) \cap (R_1 < Cap_1) \cap (R_2 < R_1)) \\ & + P((S_1 = 2) \cap (S_2 = 0) \cap (R_1 = Cap_2)) \\ & + P((S_1 = 2) \cap (S_2 = 1) \cap (R_2 = R_1)) \\ & + P((S_1 = 2) \cap (S_2 = 2) \cap (R_2 = R_1)) \end{aligned} \quad (17)$$

According to equation (6) ~ equation (16), we can express how to calculate the parameters of a_i, b_i and c_i depicted in equation (5). For example, equation (17) shows the calculation method for the parameter of a_2. Similarly, we can get the calculation methods for the parameters of b_1, b_m and C_{m-1}, a_i, b_i and c_i, which are a bit more complicated than the parameter of a_2. Finally, a_i, b_i and c_i can be expressed by the functions with the parameters of $\{A_i | 1 \le i \le m\}$ and $\{\mu_i | 1 \le i \le m\}$. Then we can get the following relation.

$$A_i = f_i\{A_1, \ldots, A_m, \mu_1, \ldots, \mu_m, \lambda_1, \ldots, \lambda_m\}, \quad 1 \le i \le m \quad (18)$$

We can calculate $\mu_1, \ldots, \mu_m$ and $\lambda_1, \ldots, \lambda_m$ according to the user behaviors analyzed in Section III. However, $A_1, \ldots, A_m$ are the targets to solve, as well as the inputs. *Particle Swarm Optimization* (*PSO*) [20] could be utilized to solve this problem. Expression (19) shows the objective function and the constraints.

$$\begin{aligned} & min \left(\sqrt{\sum_{i=1}^{m} (f_i(A_1, \ldots, A_m, \mu_1, \ldots, \mu_m, \lambda_1, \ldots, \lambda_m) - A_i)^2} \right) \\ & limit \sum_{i=1}^{m} A_i = \sum_{i=1}^{m} \lambda_i, \quad A_i > 0, \ 1 \le i \le m \end{aligned} \quad (19)$$

$A_1, \ldots, A_m$ can be calculated by expression (19). Then we can calculate the steady-state probabilities of the APs running at different states and carrying different number of users. The steady-state probability of the system shown in expression (1) can be calculated by equation (20), as shown at the top of the next page.

C. PERFORMANCE METRICS

To evaluate the efficiency of the proposed energy-saving mechanism, we introduce the following performance metrics.

$$\pi_{s_1,\ldots,s_m,r_1,\ldots,r_m} = P((S_1 = s_1) \cap \ldots \cap (S_m = s_m) \cap (R_1 = r_1) \cap \ldots \cap (R_m = r_m)) = \prod_{i=1}^{m} \pi^i_{(r_i,s_i)} \tag{20}$$

1) AVERAGE POWER CONSUMPTION

The average power consumption per unit time can be computed by equation (21). It mainly includes two parts: energy consumption of the APs running at different states and the energy consumed by state transition. The former is the sum of the steady-state probability of each AP running at each state multiplying the AP's power consumption under that state. The later is the switching frequency multiplying the energy consumed by state transition.

$$Pwr = \sum_{i=0}^{2}\sum_{j=1}^{m}\left(P\left(S_j = i\right)\cdot Pwr_i\right) + Rate_{0,1}\cdot Pwr_{0,1} + Rate_{1,2}\cdot Pwr_{1,2} \tag{21}$$

2) SWITCHING FREQUENCY

Equation (22) shows the frequency of the APs switched from the fully closed state to the energy-saving state. It is the sum of the probability of each AP running at the fully closed state multiplying the user association rate of that AP.

$$Rate_{0,1} = \sum_{i=1}^{m} P\left(S_i = 0\right)\cdot A_i \tag{22}$$

Equation (23) shows the frequency of the APs switched from the energy-saving state to the fully opened state. It is the sum of the probability of each AP running at the energy-saving state with Cap_1 users multiplying the user association rate of that AP.

$$Rate_{1,2} = \sum_{i=1}^{m} \pi^i_{Cap_1,1}\cdot A_i \tag{23}$$

Equation (24) shows the frequency of the APs switched from the energy-saving state to the fully closed state. It is the sum of the probability of each AP running at the energy-saving state with only one user, multiplying the user departure rate of that AP, and multiplying the probability of the users of its neighbour APs (in the coverage of that AP) that are fewer than h_0.

$$Rate_{1,0} = \sum_{i=1}^{m}\left(\pi^i_{1,1}\cdot\mu_i\cdot\left(\sum_{n=0}^{h_0}\left(\pi^{i-1}_n\sum_{l=0}^{h_0-n}\pi^{i+1}_l\right)\right)\right) \tag{24}$$

Equation (25) shows the frequency of the APs switched from the fully opened state to the energy-saving state. It is the sum of the probability of each AP running at the fully opened state with $Cap_1 - h_1 + 1$ users multiplying the user departure rate of that AP.

$$Rate_{2,1} = \sum_{i=1}^{m}\left(\pi^i_{Cap_1-h_1+1,2}\cdot(Cap_1 - h_1 + 1)\cdot\mu_i\right) \tag{25}$$

As depicted in equation (26), we can get the switching frequency of the APs.

$$Rate = Rate_{0,1} + Rate_{1,2} + Rate_{2,1} + Rate_{1,0} \tag{26}$$

3) AVERAGE AVAILABLE BANDWIDTH

The average available bandwidth per user can be calculated by equation (27). It means the average bandwidth can be assigned to each user by each AP in the coverage running at different states and carrying different number of users.

$$Bwd = \sum_{i=1}^{m}\left(\sum_{j=1}^{Cap_1}\frac{\pi^i_{j,1}\cdot Bwd_1}{j} + \sum_{j=Cap_1-h_1+1}^{Cap_2}\frac{\pi^i_{j,2}\cdot Bwd_2}{j}\right) \tag{27}$$

D. HYSTERESIS COEFFICIENTS

Two hysteresis coefficients of h_0 and h_1 are introduced to control the switching efficiency for user departures. We should determine a combination values for h_0 and h_1, which make the power consumption per unit time as low as possible, the switching frequency as small as possible, and the average available bandwidth per user as large as possible. This is a multi-objective optimization problem and a normalized approach is introduced to process this problem.

Equation (28) shows the normalized function of the average power consumption per unit time. 1) When h_0 is minimum and h_1 is maximum, the APs are not sensitive to the reduction of the associated users. Therefore, the power consumption per unit time is maximum. 2) when h_0 is maximum and h_1 is minimum, an AP will be switched to the closed state once the number of associated users decreases to 0, and an AP will be switched to the energy-saving state once the number of associated users decreases to Cap_1. In this case, the power consumption per unit time is minimum. After normalized process by equation (28), the larger the power consumption per unit time is, the smaller the value of Pwr_{norm} is, and vice versa.

$$Pwr_{norm}\left(h_0, h_1\right) = \frac{Pwr(h_0^{min}, h_1^{max}) - Pwr(h_0, h_1)}{Pwr(h_0^{min}, h_1^{max}) - Pwr(h_0^{max}, h_1^{min})},\quad Pwr_{nor} \in [0, 1] \tag{28}$$

Similarly, we can get the normalized functions for the switching frequency and the available bandwidth per user shown in equation (29) and equation (30) respectively.

$$Rate_{nor}\left(h_0, h_1\right) = \frac{Rate(h_0^{max}, h_1^{min}) - Rate(h_0, h_1)}{Rate(h_0^{max}, h_1^{min}) - Rate(h_0^{min}, h_1^{max})},\quad Rate_{norm} \in [0, 1] \tag{29}$$

$$Bwd_{norm}(h_0, h_1) = \frac{Bwd(h_0, h_1) - Bwd(h_0^{min}, h_1^{max})}{Bwd(h_0^{min}, h_1^{max}) - Bwd(h_0^{max}, h_1^{min})}, \quad Bwd_{norm} \in [0, 1] \tag{30}$$

Expression (31) shows the multi-objective optimization function and its constraints. Since the solution space of $\{h_0, h_1\}$ is not big, the problem is easy to solve.

$$\begin{aligned} &Max\ (Bwd_{norm}(h_0, h_1) \cdot Pwr_{norm}(h_0, h_1) \cdot Rate_{norm}(h_0, h_1)) \\ &limit\ 0 \leq h_0 \leq Cap_1, \quad 0 \leq h_1 \leq Cap_1 \end{aligned} \tag{31}$$

VI. NUMERICAL AND EXPERIMENTAL ANALYSIS

We select four neighbour classrooms as the experimental scenario. As depicted in Fig. 5, users in each classroom (e.g., C_2) can only associate with the AP deployed in that room (i.e., AP_2 in C_2) and the APs in the neighbour rooms (i.e., AP_1 in C_1 and AP_3 in C_3). APs in other rooms (i.e., AP_4 in C_4) cannot be detected and associated with due to the low *RSSI* (lower than $-75dBm$). According to the *AC* logs gathered from March 13th to March 17th in 2017, we can not only determine the values of h_0 and h_1, but also evaluate the efficiency of the proposed energy-saving mechanism.

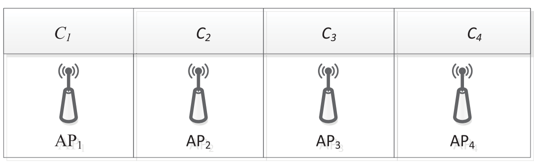

FIGURE 5. The experimental scenario.

TABLE 2. Parameter settings.

Parameters	Values
$Pwr_i,\ i \in \{0,1,2\}$	$Pwr_1 = 0,\ Pwr_2 = 6W,\ Pwr_1 = 12W$
$Pwr_{0,1}$	$600J$
$Pwr_{1,2}$	$300J$
$Cap_i,\ i \in \{0,1,2\}$	$Cap_0 = 0,\ Cap_1 = 20,\ Cap_1 = 40$
$Bwd_i,\ i \in \{0,1,2\}$	$Bwd_0 = 0,\ Bwd_1 = 100Mbps,\ Bwd_i = 200Mbps$

A. PARAMETER SETTINGS

Table II shows the parameters that are used in the evaluation. According to the specifications of *H3C WA4600 i* [21] (deployed in the studied WLAN), the energy consumption of the whole AP is less than 12.95 W. We set the energy consumption of the AP running at the fully opened state to 12 *W*, and assume that the energy consumption is 6 *W* when the AP runs at the energy-saving state. Power consumption caused by state transition is estimated based on the time needed to switch on an AP. It will take 1 to 2 minutes to conduct some initial operations for a newly opened AP [7], such as configuration, calculation, etc. We assume that the power consumption is 10 *w* during the switch-on process and the switch-on time is 90 *s*. So an AP consumes 900 *J* when it is switched from the fully closed state to the fully opened state.

TABLE 3. Parameters for the models.

C_i	$\lambda_i(s^{-1})$	$1/\mu_i$ (minute)	$A_i(s^{-1})$
C_1	0.004401473	52.01271186	0.004299061
C_2	0.004327808	53.18965518	0.004510787
C_3	0.00441989	56.20171674	0.004233731
C_4	0.004259669	52.3275862	0.004365261

In this study, we assume that the APs only can be switched from the fully closed state to the energy-saving state, or from the energy-saving state to the fully opened state. So we divide the 900 *J* into two parts, i.e., 600 *J* and 300 *J* for the two switching processes respectively. The association upper limit of each AP under different states can be set according to the analysis of the up-to-date traces [5]. As shown in Table III, parameters of the models for each classroom are calculated, including user arrival rate (λ_i), average session length $1/\mu_i$ and user association rate A_i. In this study, we use *PSO* to calculate the user association rates of the APs. The precision values of the user association rates with different iterations are calculated and the results of iterating 300 times with the precision of 8.727×10^{-17} are utilized.

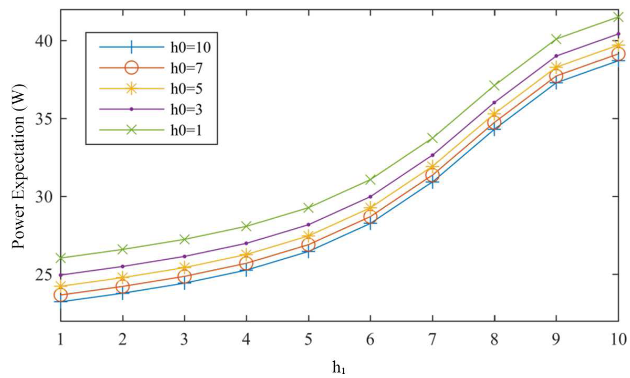

FIGURE 6. Power consumption per unit time with different h_0 and h_1 settings.

B. HYSTERESIS COEFFICIENTS DETERMINATION

As depicted in Fig. 6, the power consumption per unit time increases with the decrease of h_0. This is because when the users of an AP running at the energy-saving state decrease to 0, the AP can be closed only when the users of its neighbour APs (in the coverage of that AP) are fewer than h_0. Therefore, if h_0 is set a small value, the AP is hard to meet the condition of being switched from the energy-saving state to the fully closed state. As a result, more energy will be consumed. The hysteresis coefficient of h_1 shows different influence on the power consumption. When an AP is running at the fully opened state, it will be switched to the energy-saving state when the associated users changing from $Cap_1 - h_1$ to $Cap_1 - h_1 - 1$. Therefore, when h_1 is set to a large value, the AP is hard to meet the condition of being switched from the fully opened state to the energy-saving state. As a result, more energy will be consumed. In addition, we find that the power consumption is more affected by h_1 compared with h_0.

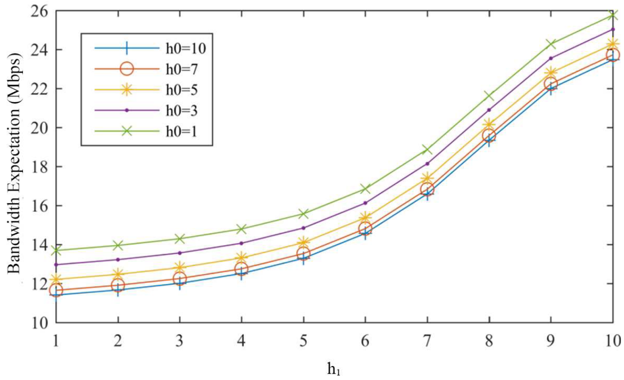

FIGURE 7. **Available bandwidth per user with different h_0 and h_1 settings.**

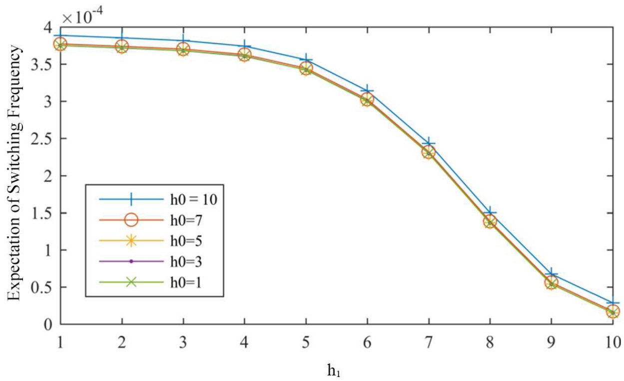

FIGURE 8. **Switching frequency per unit time with different h_0 and h_1 settings.**

This is because switching between fully opened state and energy-saving state is more frequent than that of between energy-saving state and fully closed state.

As depicted in Fig. 7, the available bandwidth per user increases with the decrease of h_0. This is because the condition of being switched from the energy-saving state to the fully closed state is hard to meet when h_0 is set to a small value. As a result, the APs running at the energy-saving states can provide more bandwidth for the users. Different from h_0, the available bandwidth per user increases with the growth of h_1. If h_1 is set to a large value, the condition of being switched from the fully opened state to the energy-saving state is hard to trigger. The APs running at the fully opened states can provide more bandwidth for the users. We also find that h_1 shows greater influence on the available bandwidth than h_0.

As shown in Fig. 8, the switching frequency per unit time decreases with the decrease of h_0, and presents an obvious decline trend with the growth of h_1. The reasons are attributed to the switching conditions become harder to meet with the decrease of h_0 and with the growth of h_1. It is also can be seen that h_1 has greater impact on the switching frequency compared with h_0.

After the analysis of the relations between the hysteresis coefficients and power consumption, available bandwidth

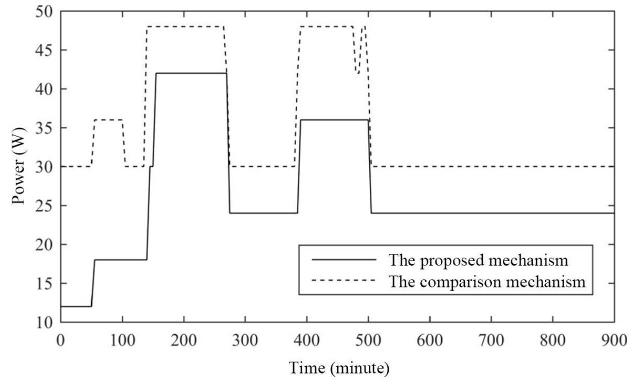

FIGURE 9. **Power consumption at each time point.**

and switching frequency, a combination of $\{h_0 = 4, h_1 = 7\}$ is determined according to the multi-objective optimization function and its constraints shown in expression (31).

C. PERFORMANCE EVALUATION

The traces from 7:30 am to 10: 30 pm on March 16 2017 are used to evaluate the efficiency of the proposed mechanism. A static energy-saving strategy is chosen to conduct a comparison analysis [8]. The comparison mechanism schedules the APs to serve the arrival users according to the historical user association records (from 6 March 2017 $\sim$ to March 10 2017). The main objective of the comparison mechanism is to provide completed coverage to satisfy the user needs.

As shown in Fig. 9, the proposed mechanism outperforms the comparison mechanism from the perspective of power consumption. The comparison algorithm schedules the APs' states according to the maximum associated users of each AP observed from the historical traces, which cannot well satisfy the dynamics of the user needs. The proposed mechanism switches on/off the APs according to the user arrivals and departures dynamically. Experimental results show that during the experimental periods, the energy consumed by the proposed mechanism is 1441604 J, while 1904833 J is needed for the the comparison mechanism. The energy can be saved by 24.3% if the proposed mechanism is utilized. More importantly, the energy consumption caused by state transition is considered in this study. Two hysteresis coefficients $\{h_0 = 4, h_1 = 7\}$ are introduce to avoid adjusting the APs too often. Experimental results show that the proposed mechanism needs 12 times of state transitions, while the comparison mechanism needs 14 times of state transitions. The switching frequency can be reduced by 14.3% while achieving a better energy-saving effect.

Fig. 10 shows the evaluation results of the available bandwidth per user at each time point. During the first 120 minutes, the comparison mechanism performs better than the proposed mechanism. As statistics, the associated users during the period of March 16 are much fewer than the associated users extracted from the historical traces (from March 6 $\sim$ to March 10). As a result, the comparison mechanism

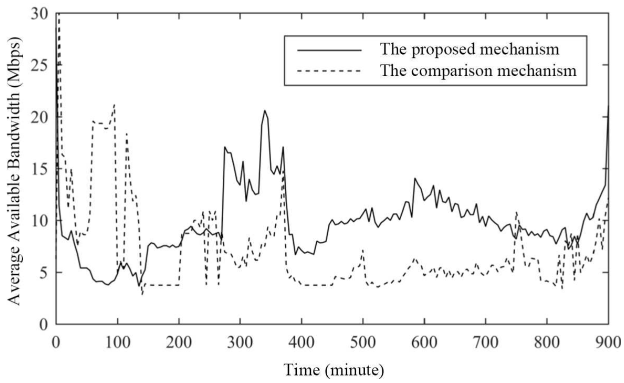

FIGURE 10. **Available bandwidth per user at each time point.**

could provide more capacity than the proposed mechanism. For example, some APs could run at the energy-saving states according to the real-time user needs, but they are fully opened according to the historical association records. After the first 120 minutes, the proposed mechanism outperforms the comparison mechanism. This is because the proposed mechanism switches on/off the APs according to the user needs, which could make the users equally distributed across the APs. In addition, due to the introduction of h_0 and h_1, state transition is a bit laggard to the changes of associated users. For example, when the users of an AP decrease to 0, the AP will not be closed at once. The arrival users can still associate with it even if other APs in the coverage have the capacity to carry these users. In summary, the proposed mechanism can balance the number of users associated with each AP and the users can get higher bandwidth on average. Through deep analysis, we find that the available bandwidth per user of the proposed mechanism is 9.67 *Mbps*, while the average available bandwidth provided by the comparison algorithm is 7.06 *Mbps*. Using our mechanism, the available bandwidth per user can be improved by 27.8%.

VII. CONCLUSIONS

In this paper, we propose a state transition-aware energy-saving mechanism for dense WLANs in buildings. First of all, up-to-date user behaviors are investigated. Then, the proposed energy-saving mechanism is described and modeled. At last, we prove the effectiveness of the proposed mechanism through an experimental analysis. Results show that the energy consumption is reduced by 24.3%, and the average available bandwidth is increased by 27.8%. Meanwhile the switching frequency is reduced by 14.3% as well.

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