Power Saving Scheme by Distinguishing Traffic Patterns for Event-Driven IoT Applications

Shenji Luan[1], Jianrong Bao[1,2*], Chao Liu[1], Jie Li[1] and Deqing Zhu[3]
[1]School of Information Engineering, Hangzhou Dianzi University
Hangzhou, Zhejiang, 310018-China
[e-mail: {luanshenji, baojr, liuchao, lijie}@hdu.edu.cn]
[2] National Mobile Communications Research Laboratory, Southeast University
Nanjing, Jiangsu, 210096-China
[3]Education Technology Center, Hangzhou Normal University
Hangzhou, Zhejiang, 310036-China
[e-mail: dqzhu@hznu.edu.cn]
*Corresponding author: Jianrong Bao

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Abstract

Many Internet of Things (IoT) applications involving bursty traffic have emerged recently with event detection. A power management scheme qualified for uplink bursty traffic (PM-UBT) is proposed by distinguishing between bursty and general uplink traffic patterns in the IEEE 802.11 standard to balance energy consumption and uplink latency, especially for stations with limited power and constrained buffer size. The proposed PM-UBT allows a station to transmit an uplink bursty frame immediately regardless of the state. Only when the sleep timer expires can the station send uplink general traffic and receive all downlink frames from the access point. The optimization problem (OP) for PM-UBT is power consumption minimization under a constrained buffer size at the station. This OP can be solved effectively by the bisection method, which demonstrates a performance similar to that of exhaustive search but with less computational complexity. Simulation results show that when the frame arrival rate in a station is between 5 and 100 frame/second, PM-UBT can save approximately 5 mW to 30 mW of power compared with an existing power management scheme. Therefore, the proposed power management strategy can be used efficiently for delay-intolerant uplink traffic in event-driven IoT applications, such as health status monitoring and environmental surveillance.

Keywords: internet of things, power saving, event driven, uplink bursty frame, constrained buffer size

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1. Introduction

With rapid development in Internet of Things (IoT) technologies, the embeded electronics applications, such as consumer electronics devices, sensors related industrial apparatuses and so on, have gradually connected to the Internet widely and wirelessly. These practical applications are suited for diverse environments and requirements, wherein no adequate coverage can be provided by a single wireless comunication standard. Nowadays, Wi-Fi is one of the most commonly used wireless Internet technologies. However, its practical applications in IoT are limited due to its high power consumption and limited bandwidth. New silicon chips and modules have been developed to address these limitations. These chips and modules are used to integrate Wi-Fi technology with low power into embedded IoT apparatuses; they are also used in battery-operated devices [1]-[3].

Applications in IoT often defined the latency response. However, the latency easily influenced the maximum sleep period of a system, in which an IoT device either stayed and connected to a network or reconnected after a predefined period [4]. For example, a temperature sensor updated the server by the measured temperature at dozes of minutes, but the latency response was not constrained in practice. Therefore, the temperature-sensor application should operate in a low-duty ratio and thus reduce power consumption. However, if this practicality is needed to sound an alarm as soon as the temperature exceeds a threshold, the latency response should last as extremely short as possible. In other words, the sensor node should immediately send back the emergency information to the IoT network. This process consumes considerable energy. Therefore, a tradeoff is needed to ensure that the application satisfies the requirement while maintaining lower power consumption in the node.

For energy conservation in a station, a power-saving mechanism by sleep control has saved much terminal energy at cost of some extra packet delay [5], [6]. Extra energy consumption is required to achieve low packet delay. One factor that affect packet delay is the functioning of a station in sleep mode. Traditionally, a station cannot transmit a frame at any time, and it has much low power consumption [7]. In [8], a large amount of energy was saved by either caching data packets or permitting the station to be wakened up rarely. Thus, all cached data packets are retrieved within one beacon interval under some network traffic. Intelligent-power-save-mode, which decides dynamic activation times based on the state of mobile users, was used in [9] to enhance the power conservation of a decision method. A scheduling policy was proposed in [10] to assign access points (APs) to different sub-clusters. Thus, APs could control Wi-Fi stations properly to have proper handovers of sleep and activity and avoid the overlapping time of packet receiving. Power consumption is also improved. Akkaya *et al.* [11] developed an energy-aware method to route the delay-constrained data. A delayed wakeup scheme was proposed in [12], wherein one beacon interval (BI) was divided into n such sub-BIs. On the basis of the amount of backlogged traffic, an AP identifies and specifies excess stations to sleep immediately. These stations are eventually awakened at a non-congested sub-BI. The above methods are power management strategies employed to reduce the delay of AP buffer, and they are unsuitable for uplink traffic in WLANs. Under the assumption of an uplink scenario, further energy-saving mode (FESM) was presented and explained in the IEEE 802.11ah standard to cut channel congestion and thus save energy [13]. In FESM, when a channel is perceived as busy, the station can sleep for a random arranged sleeping window intelligently, which can be adjusted due to the channel congestion. Although the FESM could cut packet delay for use with delay-intolerant uplink traffic, it brought more energy consumption for general uplink traffic.

Generally, the delay in urgent events might bring serious casualties, as well as property loss [14], [15]. For example, an electrocardiogram (ECG) sampling signal is transmitted to a host computer within dozens of minutes, whereas an ECG alarm signal should be transmitted immediately [16]. Many similar industrial IoT applications possess a similar feature, that is, the downlink traffic is delay tolerant, while the uplink bursty traffic is not. Therefore, scholars need to construct a power management that reduces the power expenditure of sensors widely used in event-triggered sensing practice with delay-intolerant uplink traffic.

In this work, a sleep control mechanism is designed in our scheme, which enables a station to terminate the sleep mode immediately after an uplink bursty frame is generated. Only when the sleep timer expires can the station can send back the uplink general traffic. Thus, the proposed scheme can not only save energy but also meet the requirement of uplink bursty traffic delay. However, a long sleep time is preferred to allow a station to buffer numerous uplink general frames, and this requirement causes the usage of considerable memory in the station. The buffer size of an IoT station is usually limited and fixed. For example, CC3200, a commercial Wi-Fi micro controller unit chip made by Texas Instruments Corp., only has 256 KB on-chip static random access memory [17]. Hence, a power management strategy should combine the constrained buffer at the station to distribute a proper amount of buffer units and prevent buffer overflow when the station is in sleep mode. Therefore, we present an improved power management strategy that distinguishes traffic patterns to address the problems in collaborative optimization of energy consumption, delay, and memory usage. The main contributions of this work are concluded as follows:

1) A new power management strategy suitable for uplink bursty traffic (PM-UBT) is presented. The proposed PM-UBT can create a compromise between uplink bursty traffic delay and energy consumption. It can immediately send back the uplink bursty frame whether the station is in sleep mode or not. In short, this scheme can efficiently distinguish uplink bursty and general traffic.

2) A set of stochastic partial differential equations is used to analyze and explain the performance of the proposed PM-UBT. The statistics related to the operation states of the station are proposed and derived, and these include the probabilities of the station in sleep, idle, transmitting or receiving modes, the power consumption of the station, and the average number of frames temporarily cached at the station in sleep mode.

3) A sleep timer optimization model for the proposed PM-UBT is built to minimize power consumption within the constrained cache size at the station. The optimization problem (OP) is solved effectively by using the bisection method. Moreover, the performance of the proposed method is similar to that of exhaustive search but with less computational complexity.

The remainder of the manuscript is organized as below. Section 2 presents the application of PM-UBT in uplink bursty traffic under Wi-Fi. On the basis of the proposed PM-UBT scheme and the stochastic analysis results, we construct a mathematical model of the power management algorithm and deduce and analyze the statistical results of the model in Section 3. The numerical results and optimization of the sleep duration are presented in Section 4. The experimental results are also analyzed in this section, and the performance and complexity for possible practical use are discussed. The conclusions are presented in Section 5.

2. Proposed PM-UBT

Many methods can be used for the tradeoff between energy allocation optimization and systematic robustness. A feasible scheme of energy saving is specific to the used in link-layer level. An example is the power-save mode in the 802.11 application, which enables an IoT embeded device to notify the access point (AP) to be in a energy efficient mode [18]. Through this means, the AP caches traffic data for the IoT device, namely, the station, and permits the device to select for this traffic with ease. The beacon frame includes the traffic indicator map (TIM) that announces the stations with frames cached at the AP. The device is then divised to wake up only due to these packets, thus saves the energy. And the main shortcoming of the scheme is that the communication between the embeded IoT device and the AP is confined to the sleep time of the IoT device, and it increases latency.

In PM-UBT, the station transmits right away when an uplink bursty frame arrives at its transmission cache regardless of whether the sleep period has expired or not. The station could send a general uplink frame only after a sleep timer has expired. Therefore, the proposed scheme can reduce uplink bursty traffic delay and save energy. The timelines of PM-UBT are illustrated in **Fig. 1**, where the vertical lines intersecting the horizontal timelines is represented as the beacons; a beacon interval (BI) exists between them. Each BI includes a TIM being notified by the AP. "TIM: 1" means that AP has downlink frames in its buffer, and "TIM: 0" represents no frame is buffered. Each triangle means the waking up process of a station. PM-UBT distinguishes the bursty frame from the general frame in the uplink traffic. At the fifth beacon interval, an uplink general frame is generated (**Fig. 1**), but the station remains in sleep mode. When an uplink bursty frame is generated, the frame is transmitted immediately to the AP. Thus, the bursty frame delay in milliseconds can be guaranteed for practical applications. The station returns to sleep mode until the sleep timer expires at the seventh beacon interval. The station sends the uplink general frame back to the AP. Therefore, PM-UBT can balance energy consumption and uplink delay commendably.

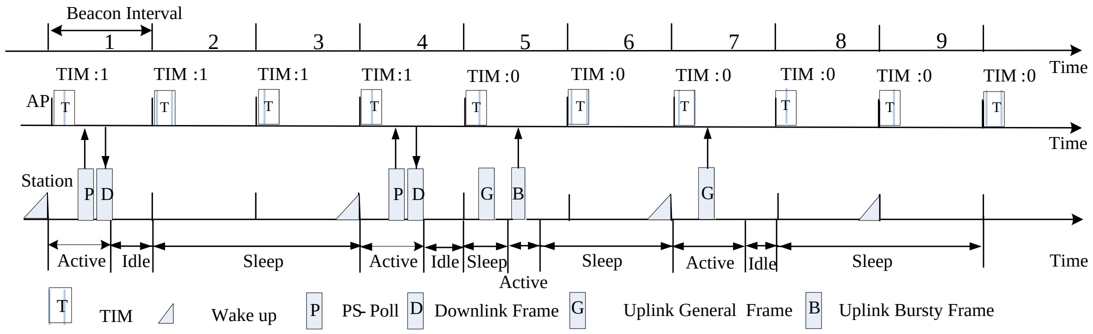

Fig. 1. Timelines of PM-UBT

3. Model and Statistics of PM-UBT

3.1 Energy Consumption Model Assumption of the Station

The energy consumption of a station depends on its operating modes, such as transmitting, receiving, or sleeping. For the sake of easy analysis, transmitting and receiving modes are combined together as active state. This active state is divided into two cases: active state awakened by the uplink bursty frame and active state due to the expiration of the sleep timer. The former is divided into sub-states $A_{b,0}$, $A_{b,1}$, $A_{b,2}$, …, $A_{b,n}$. The latter is divided into the following sub-states A_0, A_1, A_2, …, A_n. The similarity between $A_{b,n}$ and A_n is that the station has *n* other general frames for subsequent transmission and reception. The key difference between them is that only the uplink bursty frame is transmitted immediately in $A_{b,n}$, whereas the general frames are transmitted in A_n when the sleep timer has expired. Similarly, the sleep state is divided into the sub-states: D_0, D_1, D_2, …, where D_n means the station in sleep mode with *n* frames cached at the station and the AP. The transition flow diagram among the aforementioned states is figured out in **Fig. 2**, where the circles represent the states of the station and the circle labeled with "*I*" means the idle state.

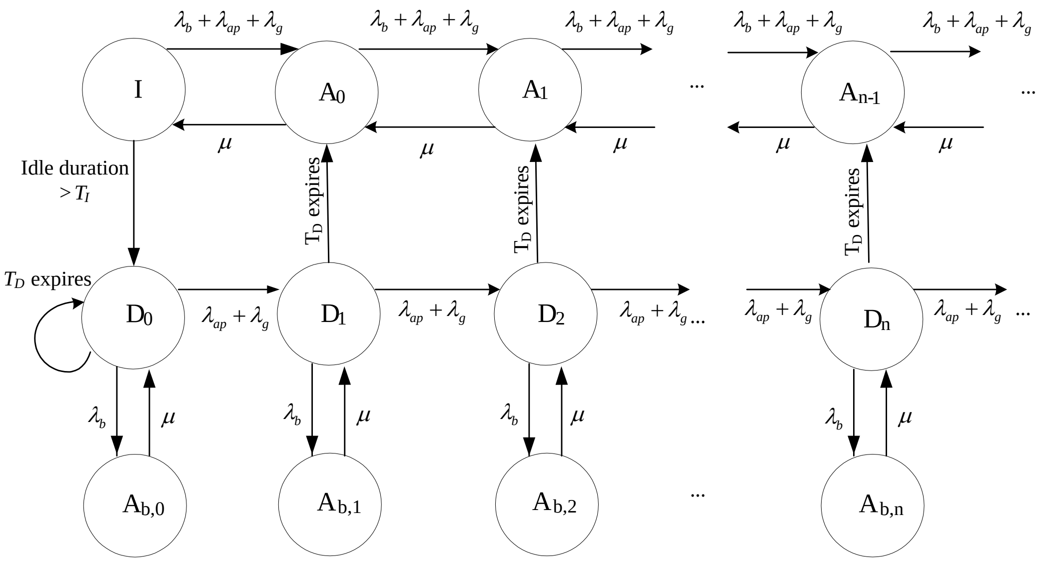

Fig. 2. Flow diagram of state transition

Similar to the situations in [19], and [20], the traffic pattern in the IoT station usually forms a Poisson Process and it is suited to be modeled as a Markov Process. The main notations and definitions involved in the model are listed in **Table 1**.

Table 1. Main notations and definitions pertaining to the model

Notations	Definitions
χ_D	Sleep period of the station with the probability density function (*pdf*) $g(x)$ and the cumulative distribution function (CDF) $G(x)$.
χ	Time consumed by the station to tranceive a frame, with *pdf* and CDF denoted by $f(x)$ and $F(x)$, respectively.
λ_{ap}	The rate of the downlink frames reach AP and also destined to the station forms a Poisson process.
λ_g	The rate of the uplink general frames arriving at the station forms a Poisson process.
λ_b	The rate of the uplink bursty frames arriving at the station forms a Poisson process.
$\lambda = \lambda_{ap} + \lambda_g + \lambda_b$	The rate of the frames genrated at the AP or the station forms a Poisson process.
$1/\mu$	The expectation of χ, which is represented as $E(\chi) = 1/\mu$.
$\tau(x)$	The hazard rate function of χ_D in [21] is $\tau(x) = g(x)/(1-G(x))$.
$\sigma(x)$	The hazard rate function of χ is denoted by $\sigma(x) = f(x)/(1-F(x))$.
$m(w,t)$	The number of frames arriving at the station forms a Poisson process with rate *w* during time *t*.

3.2 Model of PM-UBT

We denote $\boldsymbol{\Omega}$ as the set of all states of the station. $X(t)$ is its accumulated state residence time (ASRT), *i.e.*, the amount of time which the station has spent in current state until the time instance t. $\xi(t)$ denotes the state of a station at time instance t. For all states in $\boldsymbol{\Omega}$ at time instance t, a joint probability density function (*pdf*) $p_u(t,x)$ about $X(t)$ and $\xi(t)$ satisfies

$$p_u(t,x)dx = \Pr\{\xi(t)=u,\ x < X(t) \le x+dx\}. \tag{1}$$

Given the relations of state transitions during Δt in **Fig. 2** and with Δt approaching 0, we have the following differential equations for the station [21].

First, the probability that the station remains in state A_0 with the accumulated state residence time (ASRT) $x+\Delta t(x>0)$ at time instance $t+\Delta t$ is identical with the probability that the station is in state A_0 with ASRT x at time instance t. Moreover, the station remains in state A_0, and no other frame arrives during Δt. Thus,

$$\begin{aligned}&\Pr\{\xi(t+\Delta t)=A_0, x+\Delta t < X(t+\Delta t) \le x+\Delta t+dx\}\\ &=\Pr\{\xi(t)=A_0, x < X(t)\le x+dx\}(1-\lambda\Delta t)(1-\sigma(x)\Delta t)\end{aligned}. \tag{2}$$

From this result, the following can be further derived.

$$p_{A_0}(t+\Delta t, x+\Delta t)dx = p_{A_0}(t,x)dx(1-\lambda\Delta t)(1-\sigma(x)\Delta t). \tag{3}$$

Then,

$$\frac{p_{A_0}(t+\Delta t,x+\Delta t)-p_{A_0}(t+\Delta t,x)}{\Delta t}+\frac{p_{A_0}(t+\Delta t,x)-p_{A_0}(t,x)}{\Delta t}=-p_{A_0}(t,x)(\lambda+\sigma(x))+\frac{o(\Delta t)}{\Delta t}. \tag{4}$$

By setting Δt to approach 0, we achieve

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\lambda+\sigma(x)\right]p_{A_0}(t,x)=0. \tag{5}$$

Second, the probability that the station is in state A_n (n=1, 2, …) with ASRT $x+\Delta t$ (x>0) at time instance $t+\Delta t$ is the same as the sum of the probabilities, as follows:

1) The station stays in state A_n with ASRT x at time instance t, and the station is still in state A_n without new frame arrival during Δt.

2) The station stays in state A_{n-1} with ASRT x at time instance t, and a new frame incomes during Δt. These state transitions during time interval Δt yields

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\lambda+\sigma(x)\right]p_{A_n}(t,x)=\lambda p_{A_{n-1}}(t,x) \qquad (n=1,2,\cdots). \tag{6}$$

Third, the probability that the station is in state D_0 with ASRT $x+\Delta t$ (x>0) at time instance $t+\Delta t$ is the same as the probability that the station stays in state D_0 with ASRT x at time instance t. The station remains in state D_0, and no other frame arrives during Δt. Thus,

$$[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\lambda+\tau(x)]p_{D_0}(t,x)=0. \tag{7}$$

Fourth, the probability that the station is in state D_n (n = 1, 2,…) with ASRT $x+\Delta t$ (x>0) at time instance $t+\Delta t$ is the same as the sum of the probabilities, given the following:

1) The station stays in state D_n with ASRT x at time instance t, and the station remains in state D_n without any arrival of a frame during Δt.

2) The station is in state D_{n-1} with ASRT x at time instance t, and only a general frame arrives during Δt. These state transitions during time interval Δt yields

$$\begin{aligned}&p_{D_n}(t+\Delta t, x+\Delta t)dx\\&=\Pr\{\xi(t+\Delta t)=\mathrm{D_n}, x+\Delta t < X(t+\Delta t)\le x+\Delta t+dx\}\\&=\Pr\{\xi(t)=\mathrm{D_n}, x< X(t)\le x+dx\}(1-\lambda\Delta t)(1-\tau(x)\Delta t)\\&+\Pr\{\xi(t)=\mathrm{D_{n-1}}, x<X(t)\le x+dx\}((\lambda_{ap}+\lambda_g)\Delta t)(1\text{-}\lambda_b\Delta t)(1-\tau(x)\Delta t)\\&=p_{D_n}(t,x)dx(1-\lambda\Delta t)(1-\tau(x)\Delta t)+p_{D_{n-1}}(t,x)dx((\lambda_{ap}+\lambda_g)\Delta t)(1-\lambda_b\Delta t)(1-\tau(x)\Delta t)\end{aligned}. \quad (8)$$

When Δt approaches 0, we obtain

$$[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\lambda+\tau(x)]p_{D_n}(t,x)=(\lambda_{ap}+\lambda_g)p_{D_{n-1}}(t,x), n=1,2,\cdots. \quad (9)$$

Fifth, the probability that the station stays in state A_0 with ASRT s ($s\le\Delta t$) at time instance $t+\Delta t$ is the same as the sum of the probabilities, and the following situations exist.

1) The station is in state A_1 with ASRT x at time instance t, and the station jumps to state A_0 without frame arrival during Δt.

2) The station stays in state I at time instance t, and the accumulated idle time is no more than T_I during Δt, but a new frame generated by the station or the AP arrives.

3) The station is in state D_1 at time instance t, and the station suspends sleeping and no additional frames arrive during Δt.

These state transitions during time interval Δt yield

$$\begin{aligned}p_{A_0}(t+\Delta t, s)\Delta t&=\Pr\{\xi(t+\Delta t)=\mathrm{A_0}, s<X(t+\Delta t)\le s+\Delta t\}\\&=(1-\lambda\Delta t)\int_0^\infty p_{A_1}(t,x)(\sigma(x)\Delta t)dx\\&+(\lambda\Delta t)P_I(t)\Pr\{\chi_I+\Delta t<T_I\,|\,\chi_I<T_I\}\\&+(1-\lambda\Delta t)\int_0^\infty p_{D_1}(t,x)(\tau(x)\Delta t)dx\end{aligned}. \quad (10)$$

When Δt approaches 0, we have

$$p_{A_0}(t,0)=\int_0^\infty p_{A_1}(t,x)\sigma(x)dx+\lambda P_I(t)+\int_0^\infty p_{D_1}(t,x)\tau(x)dx. \quad (11)$$

Sixth, the probability that the station stays in state A_n (n = 0, 1, 2,…) with ASRT s($s\le\Delta t$) at time instance $t+\Delta t$ is the same as the sum of the probabilities, and the results are as follows.

1) The station is in state A_{n+1} with ASRT s at time instance t, and no new frame arrives but the station jumps to state A_n (*i.e.*, the station just completes receiving or delivering a frame) during Δt.

2) The station stays in state D_{n+1} with ASRT s at time instance t, and the sleep duration expires during Δt.

Therefore, we obtain

$$p_{A_n}(t,0)=\int_0^\infty p_{A_{n+1}}(t,x)\sigma(x)dx+\int_0^\infty p_{D_{n+1}}(t,x)\tau(x)dx \qquad (n=0,1,2,\cdots). \quad (12)$$

Seventh, the probability that the station stays in state D_0 with ASRT s($s\le\Delta t$) at time instance $t+\Delta t$ is the same as the sum of the probabilities, and the results are as follows.

1) The station is in state D_0 with ASRT s at time instance t, and no new frame arrives while the sleep period expires (*i.e.*, a new sleep duration begins) during Δt.

2) The station is in state I at time instance t, and the accumulated idle time surpasses T_I but no extra frame arrives during Δt.

Thus, there is

$$p_{D_0}(t+\Delta t, s)\Delta t = \Pr\{\xi(t+\Delta t) = \mathrm{D}_0, s < X(t+\Delta t) \le s+\Delta t\}$$
$$= (1-\lambda\Delta t)P_I(t)\Pr\{\chi_I + \Delta t \ge T_I \,|\, \chi_I < T_I\} + (1-\lambda\Delta t)\int_0^\infty p_{D_0}(t,x)(\tau(x)\Delta t)dx \quad . \tag{13}$$

When Δt approaches 0 (s approaches 0 as well), we obtain

$$p_{D_0}(t,0) = P_I(t)\frac{\lambda e^{-\lambda T_I}}{1-e^{-\lambda T_I}} + \int_0^\infty p_{D_0}(t,x)\tau(x)dx\,. \tag{14}$$

Eighth, noting it is impossible for the station stays in state D_n with ASRT $s(s \le \Delta t)$ at time instance $t+\Delta t$, we have

$$p_{D_n}(t,0) = 0 \quad n = 1,2,\cdots. \tag{15}$$

Ninth, the probability that the station is in state $A_{b,n}$ with ASRT $s(s \le \Delta t)$ at time instance $t+\Delta t$ is the same as the probability that the station is in state D_n with ASRT s at time instance t. The station jumps to state $A_{b,n}$ during Δt. Thus,

$$p_{A_{b,n}}(t,0) = \lambda_b \int_0^\infty p_{D_n}(t,x)dx \quad n = 0,1,2,\cdots. \tag{16}$$

Finally, the probability that the station stays in state I at time instance $t+\Delta t$ is the same as the sum of the following probabilities.

1) The station is in state I at time instance t, and the accumulated idle time does not beyond T_I and no frame arrives during Δt.

2) The station is in state A_0 with ASRT x at time instance t, and the station finishes transmitting/receiving a frame with no new frame arrival during Δt.

Therefore,

$$P_I(t+\Delta t) = P_I(t)(1-\lambda\Delta t)\Pr\{\chi_I + \Delta t < T_I \,|\, \chi_I < T_I\} + (1-\lambda\Delta t)\int_0^\infty p_{A_0}(t,x)(\sigma(x)\Delta t)dx\,. \tag{17}$$

After further derivation of Equation (17), we obtain

$$\left[\frac{d}{dt} + \frac{\lambda}{1-e^{-\lambda T_I}}\right]P_I(t) = \int_0^\infty p_{A_0}(t,x)\sigma(x)dx\,. \tag{18}$$

3.3 Statistics and Probability of PM-UBT

By solving Equations (5) to (18), we achieve the following stationary probabilities.

$$P_A = \lambda/\mu = \rho\,, \tag{19}$$

$$P_I = \frac{\lambda_b(1-\rho)(1-e^{-\lambda T_I})(1-e^{-\lambda T_D})}{\lambda_b(1-e^{-\lambda T_I})(1-e^{-\lambda T_D}) + \lambda e^{-\lambda T_I}(1-e^{-\lambda_b T_D})}\,, \tag{20}$$

$$P_D = \frac{\lambda(1-\rho)(1-e^{-\lambda_b T_D})e^{-\lambda T_I}}{\lambda_b(1-e^{-\lambda T_I})(1-e^{-\lambda T_D}) + \lambda e^{-\lambda T_I}(1-e^{-\lambda_b T_D})}\,, \tag{21}$$

where P_A, P_I, and P_D are the corresponding probabilities of the station staying in active, idle, and sleep states.

State residency probability P_A is consistent with our intuition because the mean time of transceiving a frame at the station is $1/\mu$, and the rate with which the downlink frames arrive at AP and sent to the station or the uplink frames generated at the station is λ. Thus, during time period T, the time of the transceiving of frames at the station is equal to $\lambda T/\mu$. Therefore, Equation (19) is obtained as presented above. In (19), the probability in the active state, P_A, only depends on λ and μ other than T_I and T_D. The idle time T_I can be considered as a random variable. Hence, we may tune the sleep time T_D to change the state residency probabilities of P_I and P_D.

E_{avg} and N_{Sta} represent the average power consumption of the station and the average number of cached frames at the station in sleep state, respectively. Equations (22) to (24) are then obtained.

$$E_{avg} = P_A E_A + P_I E_I + P_D E_D = \rho E_A + (1-\rho) E_D + (E_I - E_D) P_I \ . \tag{22}$$

where E_A, E_I, and E_D are the power consumptions of all stations in the above three states, respectively. By substituting Equation (20) into Equation (22), the detailed expression of E_{avg} is obtained.

$D_{i,j}$ represents the event wherein the station is in sleep state and that i uplink general frames and j downlink frames are buffered in queue-station and queue-AP, respectively, where $i, j = 0, 1, \ldots$. In addition, the frames arriving at the station and forming a Poisson process with rate ω during time t are denoted as $m(w,t)$. The probability that the station stays in state $D_{i,j}$ is calculated as follows:

$$\begin{aligned} P_{D_{ij}} &= P_D \Pr\{m\{\lambda_g, T_D\} = i\} \Pr\{m\{\lambda_{ap}, T_D\} = j\} \\ &= P_D \frac{e^{-\lambda_g T_D} (\lambda_g T_D)^i}{i!} \frac{e^{-\lambda_{ap} T_D} (\lambda_{ap} T_D)^j}{j!} \\ &= P_D \frac{\lambda_g^i \lambda_{ap}^j T_D^{\,i+j}}{i!\, j!} e^{-(\lambda_{ap}+\lambda_g) T_D} \end{aligned} \ . \tag{23}$$

Thus, the average number of buffered frames at the station in sleep state can be deduced as

$$N_{Sta} = \sum_{i=1}^{\infty} \sum_{j=0}^{\infty} i \cdot P_{D_{ij}} = \sum_{i=1}^{\infty} \sum_{j=0}^{\infty} P_D \frac{\lambda_g^i \lambda_{ap}^j T_D^{\,i+j}}{(i-1)!\, j!} e^{-(\lambda_{ap}+\lambda_g) T_D} = P_D \sum_{i=1}^{\infty} \frac{\lambda_g^i T_D^{\,i}}{(i-1)!} e^{-\lambda_g T_D} = \lambda_g T_D P_D \ . \tag{24}$$

We use Equations (22) and (24) to evaluate the energy consumption and buffer size usage at the station. The optimal parameter T_D pertaining to minimal energy consumption is calculated under a limited buffer size at the station.

4. Numerical Results and Analysis

As mentioned in Section 2, according to the fundamental power management defined in the IEEE 802.11 WLAN standard series, when a station finishes transceiving its frames, the station should remain in idle state until the next beacon arrives [18]. Idle time is considered as a random variable uniformly distributed in [0, *BI*], yielding $E(T_I) = 0.5\, BI$. As shown in [17], the IoT chip CC3200 is usually powered by a 3000 mAh, 3.6 V, lithium battery with E_A = 990 mW, E_I = 200 mW, and E_D = 44 mW. μ usually depends on the traffic and the channel condition affecting data rate. At present, 802.11a/g series support data rates varing from 6Mps to 54 Mbps. In [22] and [23], the frame transmission rates with a 1300-byte payload based on the above standard were varing from 516 frames/s to 3311 frames/s (fps). Here, μ = 500 fps is chosen as the nominal value when the data rate is at 6Mps.

The proposed PM-UBT focuses on reducing power consumption, especially for uplink bursty traffic. In IoT applications, such as environmental monitoring, the majority of traffic is uplink traffic [24]. Simulations are performed using the parameters listed in **Table 2** [25].

Table 2. Simulation parameters in the proposed PM-UBT schemes

Parameter	Value
BI (beacon interval)	0.1 s
Date rate	6 Mbps
Length of data frame	500 B
Length of ACK frame	34 B
Slot time	20 *us*
SIFS (short interframe space)	10 *us*
DIFS (distributed interframe space)	50 *us*
CWmin (minimum contention window)	31
CWmax (maximum contention window)	1023
Duration of simulation	100 s

The power consumption of the PM-UBT when λ_g / λ_b = 20, 30, 40, 50 is shown in **Fig. 3,** which reveals the following results. First, power consumption increases when λ grows, which is consistent with the fact that growth in λ causes an increase in transmitted packets, resulting in increased power consumption. Second, the station with a large λ_g / λ_b value is preferred to reduce power consumption. These phenomena can be explained as follows. For a particular λ, or a large λ_g / λ_b value, brings more general traffic than bursty traffic, thereby increasing the residence time of the station in sleep state. Thus, less power is consumed.

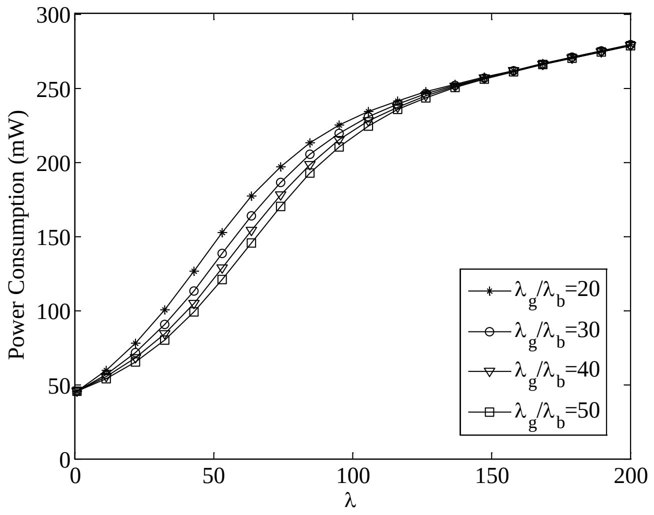

Fig. 3. Power consumption of the PM-UBT with different λ values

The impact of T_D on power consumption of PM-UBT is shown in **Fig. 4**. Power consumption at the station decreases as T_D is increased, which agrees with the above deductions of the proposed algorithm. But impacts of T_D on power consumption are weakened gradually, when λ becomes larger. The reason can be explained as follows. The station with large λ transmits so much traffic that it has less chance to sleep, which inevitably increases the power consumption.

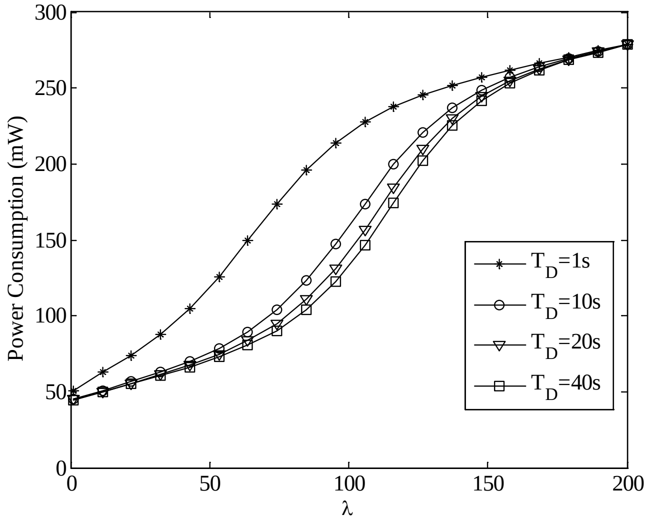

Fig. 4. Impact of T_D on the power consumption in PM-UBT

We compare the power consumption of the proposed PM-BUT with that of FESM under uplink general traffic and bursty traffic, respectively. As shown in **Fig. 5**, the FESM consumes more power than that of the PM-UBT under uplink general traffic. When the uplink general frame arrival rate λ_g is between 5 and 100 *fps*, PM-UBT can save approximately 5 mW to 30 mW of power compared with FESM. This phenomenon can be analyzed as follows. The station with FESM is awakened from sleep state whether the uplink frame is bursty or not. It enters the active state and remains in this state for a long period; thus, power expenditure increases. Such transitions may offset the gain from collision reduction. Furthermore, these two schemes consume the close amount of power when λ_g is sufficiently large. The station with a sufficiently large λ_g has little chance to sleep. Therefore, the station is in active state most of the time, but the power consumption in the two schemes is similar.

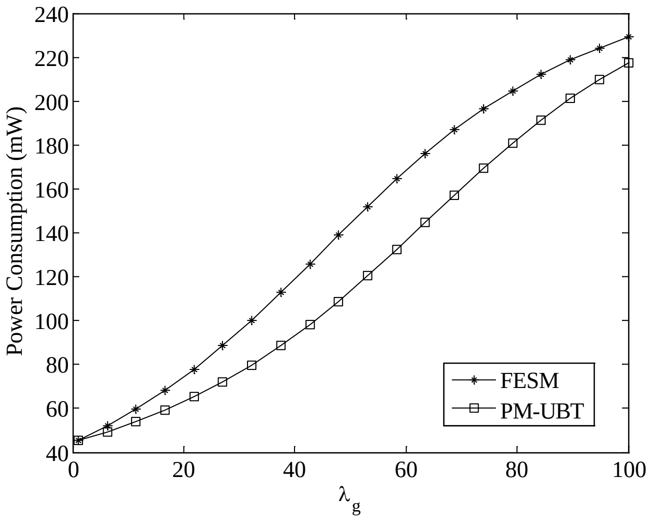

Fig. 5. Power consumption of the FESM and the PM-UBT under uplink general traffic

Then, we compared the N_{sta} , *i.e.*, the average number of buffered frames at the station in sleep state, of the PM-UBT with that of the FESM. In **Fig. 6**, the PM-UBT consumes much more memory than that of the FESM. The reason lies in the fact that the PM-UBT can distinguish the uplink bursty and also the general traffic, which causes the station to enter into the sleep state with higher probability, and thus N_{sta} is increased.

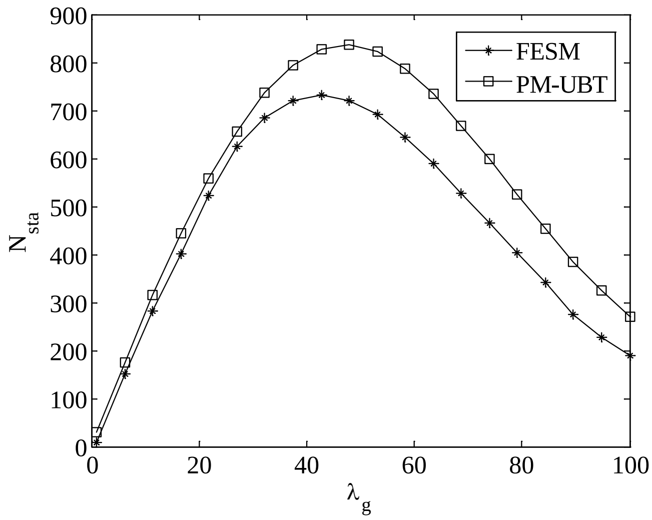

Fig. 6. Memory usage of the FESM and the PM-UBT under uplink general traffic

Then considering uplink bursty traffic in **Fig. 7**, the PM-UBT consumes the same amount of power as that of the FESM. This is because the station transmits the uplink bursty frame immediately in both schemes. Moreover, the uplink general traffic power consumption is less than that of the uplink bursty traffic under the same arrival rate. When the arrival rate is 20 *fps*, the power consumption of the FESM and the PM-UBT power consumption is about 60 mW and 70 mW, respectively, under uplink general traffic (**Fig. 5**). With the same arrival rate, the power consumption is close to 100 mW in both schemes under uplink bursty traffic (**Fig. 7**). Besides channel collision reduction, it is meaningful to distinguish the traffic pattern in event-driven IoT application.

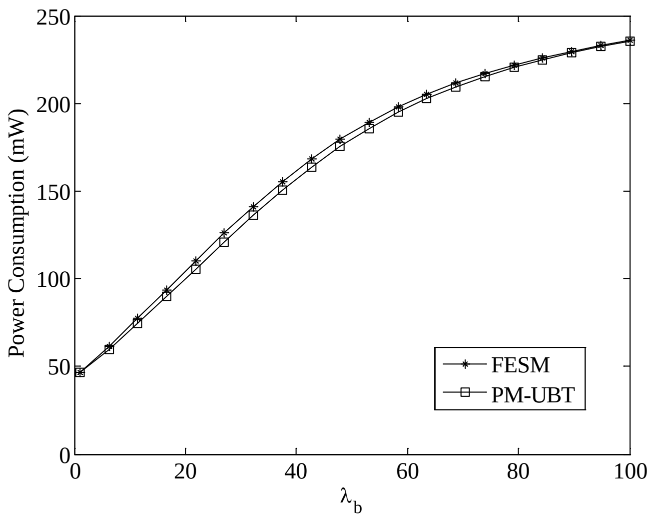

Fig. 7. Power consumption of the FESM and the PM-UBT under uplink bursty traffic

In summary, for the station with the PM-UBT scheme, distinguishing between bursty traffic and general traffic helps reduce power consumption (**Fig. 5** and **Fig. 7**).

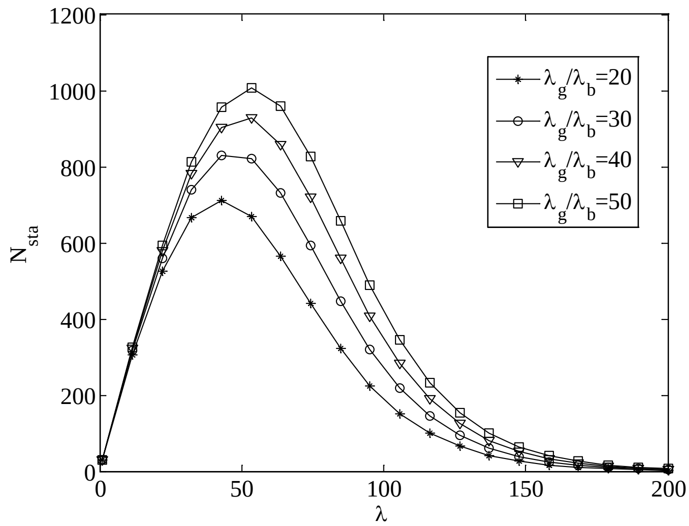

Fig. 8. Memory usage of PM-UBT

Next, we investigate the impact of λ on N_{Sta} of the station as presented in Equation (24). Let T_D = 30 s, λ_g / λ_b = 20, 30, 40, 50, and λ is variable; the simulation results are shown in **Fig. 8**. First, for a particular λ, the station with a larger λ_g / λ_b is preferred to buffer more memory given that a large λ_g / λ_b value provides long residence time in the sleep state. Second, N_{Sta} increases and then decreases when λ increases. This trend can be explained as follows. When a small λ value increases, little traffic reaches the station. Thus, the station finishes transceiving the frames quickly and it enters into the sleep state for a duration of T_D. During the sleep period, a high λ value increases the length of cached frames. Subsequently, N_{Sta} gradually increases as λ grows. Moreover, when λ is sufficiently large, the station transceives much more traffic that it has less chance to sleep, thus reducing N_{Sta}.

In the applications of IoT based on Wi-Fi, power management should extend the operation time considerably when batteries are used to power an embedded device. However, long sleep time of a station requires much memory to buffer the uplink general frames. This problem can be solved by modeling the OP shown in Equation (25). This modeling enables the PM-UBT scheme to achieve minimum power consumption of the station while maintaining the memory buffer under a given bound by selecting the optimal parameters of the sleep timers.

$$\begin{aligned} &Min \quad E_{avg} \\ &w.r.t. \quad T_D \\ &s.t. \quad N_{Sta} \le \Gamma; \\ &\qquad T_D = iBI, i = 1, 2, \cdots, N \end{aligned} \qquad (25)$$

where Γ is the maximum length of frames on the buffer at the station in sleep state.

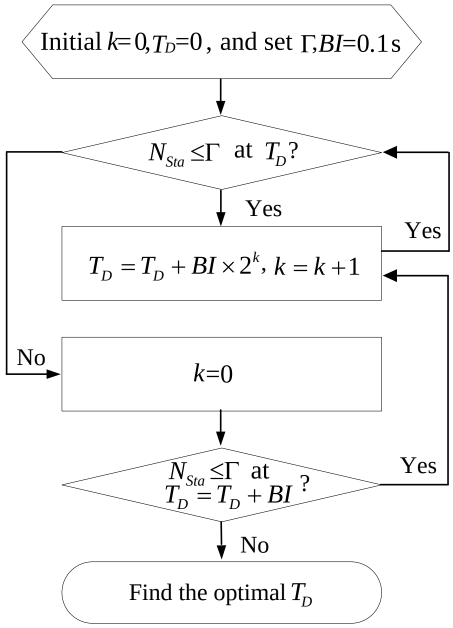

Fig. 9. Diagram of the proposed bisection method

The optimal solution is obtained through an exhaustive search. However, the processor used in this method requires much time and power. Power consumption is assumed to decrease monotonically with the increase in T_D. In addition, we notice that the longer the station remains in sleep state, the more uplink general frames are cached in the buffer. We can use the bisection method to solve OP effectively. A diagram of the bisection method is shown in **Fig. 9**. Moreover, T_D is fixed as multiples of *BI*. A two bytes field is applied in the management frame of the listen interval (*LI*), *i.e.*, the number of *BI* for an energy-saving station, and the maximum *LI* value is limited to 2^{16}-1 = 65535 [18].

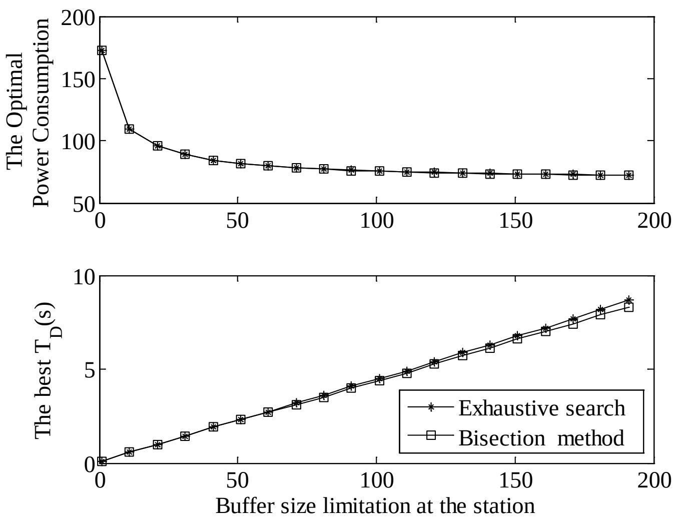

Fig. 10. Optimal power consumption under different memory limitation

In health status monitoring application scenarios, the ECG sampling rate is 1 KHz, and the quantization precision is 16 bit, that is, 2 KB/s per channel [26]. When the station includes eight ECG channels and the data frame size is 500 bytes, the uplink general frame arrival rate is 32 *fps*. When Γ varies and λ = 32 *fps*, we can solve the above OP, and the key is shown in **Fig. 10**. First, power consumption can be gradually reduced (See the upper portion in **Fig. 10**) by increasing the corresponding T_D (See the bottom portion in **Fig. 10**) as the memory size limitation Γ grows. When Γ = 10 frames, the optimal power consumption is approximately 115 mW at T_D = 0.5 s. In addition, when Γ = 50 frames, power consumption is reduced to approximately 80 mW at T_D = 2.2 s. Alternatively, we can reduce the power consumption by setting the station sleep much longer when more memory is to be used at the station. Second, the performance of the bisection method is similar to that of exhaustive search. Thus, the bisection method is suitable for practical engineering.

In summary, the proposed PM-UBT, together with the OP given in Equation (25), can save power with limited memory space at the station. Moreover, PM-UBT immediately sends uplink bursty frames.

5. Conclusion

We present a PM-UBT scheme for IoT stations to achieve a compromise between uplink bursty traffic delay and power consumption. The proposed PM-UBT significantly reduces power consumption compared with FESM under the constraint of uplink bursty frame delay. In the proposed PM-UBT, power consumption can be greatly reduced, and the memory buffer size in the station is controlled within limited space by modifying the parameters of the embedded sleep timers. Thus, PM-UBT contributes to the practical design guideline of delay-intolerant uplink traffic in IoT applications, such as health status monitoring and environmental monitoring [27]. In the future work, by employing collaborative optimization of the parameters with intelligence in each layer [28], we can further enhance the performance of this power management strategy to achieve improved practical usages of IoT in event-driven scenarios.

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Shenji Luan received his B.S. and M.S. degrees both in Communication Engineering from Hangzhou Dianzi University, Hangzhou, Zhejiang, China, in 2002 and 2005, respectively. He received his Ph.D. degree in Control Science and Engineering from Zhejiang University of Technology, Zhejiang, China, in 2015. He is working in the Information Engineering School, Hangzhou Dianzi University. His current research interests include power management and data communications for wireless networks including wireless local area network, wireless sensor network, and cellular network.

Jianrong Bao received his B.S. degree in Polymer Materials & Eng., and M.S. degree from Zhejiang University, Hangzhou, China, in 2000 and 2004, respectively. He received his Ph.D. E.E. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2009. He has visited and studied at the Department of Electrical Engineering, Columbia Univesity in the City of New York, USA, as a Visiting Scholar under the supervision of the IEEE Fellow, Prof. Xiaodong Wang in 2015. He is currently a professor in Information Engineering School, Hangzhou Dianzi University, Hangzhou, Zhejiang, China. He is also a Visiting Scholar at the National Mobile Communications Research Laboratory, Southeast University, Nanjing, China. His research interests include space communications, cooperative sensor networks, *etc*.

Chao Liu received the B.S.E.E. and Ph.D.E.E. from the School of Electronic Information and Communications, Huazhong University of Science & Technology, Wuhan, China, in 2000 and 2005, respectively. He is currently an associate professor in Information Engineering School, Hangzhou Dianzi University, Hangzhou, Zhejiang, China. His research interests include modern wireless communication and coding, MIMO multi-user detection and so on.

Jie Li received her B.S. E.E. and the M.S.E.E. degree from the School of Computer and Communication Engineering, China University of Petroleum, School of Communication Engineering, Hangzhou Dianzi University, Hangzhou, China, in 1997 and 2003, respectively. She is with the Information Engineering School, Hangzhou Dianzi University, Hangzhou, Zhejiang, China. Her main research interests include wireless communications, communication signal processing, network communications, information security, *etc*.

Zhu Deqing received his B.S. degree in Science and Technology of Electronic Information from Shandong University, Weihai, China, in 2003, his M.S. degree in Circuits and Systems from Zhejiang University, Hangzhou, China in 2010, and his Ph.D. degree in Control Science and Engineering from Zhejiang University of Technology, Hangzhou, China in 2016, respectively. Now he is with the Education Technology Center, Hangzhou Normal University, Hangzhou, Zhejiang, China. His research interests include mobility management for wireless networks and performance analysis of wireless networks, *etc*.