An Energy-Efficient Scheme for IoT Networks

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***Abstract*:** With the advent of the Internet of Things era, "things-things interconnection" has become a new concept, that is, through the informatization and networking of the physical world, the traditionally separated physical world and the information world are interconnected and integrated. Different from the concept of connecting people in the information world in the Internet, the Internet of Things extends its tentacles to all aspects of the physical world. The proposed algorithm considers the periodical uplink data transmission in IEEE 802.11ah LWPAN and a real-time raw settings method is used. The uplink channel resources were divided into Beacon periods after the multiple nodes send data to the access point. First, the access point predicted the next data uploading time during the Beacon period. In the next Beacon period, the total number of devices that will upload data is predicted. Then, the optimal read-and-write parameters were calculated for minimum energy cost and broadcasted such information to all nodes. After this, the data is uploaded according the read-and-write scheduling by all the devices. Simulation results show that the proposed algorithm effectively improved the network state prediction accuracy and dynamically adjusted the configuration parameters which results in improved network energy efficiency in the IoT environment.

***Keywords*:** IoT, network state prediction, energy-efficient networks, LWPAN, periodical uplink data transmission**.**

1. Introduction

The Internet of Everything has developed rapidly, and wireless Internet of Things applications have shown an explosive growth trend, and a huge number of M2M terminals have appeared [1-10]. Research predicts that the number of M2M terminals will increase at an annual rate of 20% [11-19]. The current low-power IoT communication technologies are mainly divided into two categories, namely, personal wireless local area network (WPAN) and low-power wide area network (LWPAN) [20]. WPAN mainly provides small-range medium data rate access, while LWPAN mainly focuses on low data rate, long distance, and large area coverage. Typical WPAN networks include ZigBee and Bluetooth Low Energy (BLE) [21], and LWPAN includes Sigfox, LoRa, NB-IoT, etc.

The IEEE 802.15.4ah and BLE standards focus on solving the problem of low power consumption, but the transmission distance is short, and the communication rate is low. LoRa, SigFox and NB-IoT standards mainly solve the problem of long-distance transmission, but the system throughput rate is low. In response to the above problems, the IEEE organization confirmed the IEEE 802.11ah standard in early 2017, considering the needs of long-distance transmission and higher throughput.

The main features of the IEEE 802.11ah standard include: working in the Sub-1 GHz unlicensed frequency band, a lower carrier frequency can achieve a longer coverage distance; a higher communication rate, with a minimum rate of 100 kbit/s and a maximum rate of up to 78 Mbit/s; an AP can support up to 8,191 users to access network terminals.

However, a large number of users will cause serious conflicts. Therefore, IEEE 802.11ah designed the RAW mechanism to allow only some terminals to access in a certain period, thereby reducing channel conflicts and reducing energy waste caused by conflicts.

However, the access window setting, and the number of access terminals are important factors that affect the overall energy cost and need to be optimized for specific applications.

In response to this problem, literature [22-23] proposed an analysis model to study and calculate the energy consumption and throughput rate of IEEE 802.11ah systems. The authors in [24] established a strategy to prolong the sleep time of the terminal based on the enhanced distributed channel access (EDCA) method and forced to sleep the terminal with multiple access time slots and continuous backoff. This solution can effectively reduce the number of conflicts, prolong the sleep time of the terminal, and reduce the system power consumption overhead, but this method will cause a longer data transmission delay. The authors in [25] proposed a scheme to optimize the number of time slots in the RAW group according to the number of access terminals, which improves energy efficiency, but the number of access terminals needs to be known, which makes practical applications difficult. The authors in [26] used a multi-objective game optimization method to design and study the influence of the number of uplink and downlink time slots on the system power consumption and obtain the optimal number of channel access time slots. This solution can ensure that the terminal stays in a sleep state for a long time, but requires accurate system clock synchronization, which is difficult. In [27], for a multi-user massive MIMO system with a partially connected radio transmission system structure, a joint optimization problem of calculation and communication power was formulated. Literature [28-289] proposed a cellular network energy efficiency model considering the spatial distribution of traffic load and power consumption and analyzed the energy efficiency of the network.

The above studies have not considered the change characteristics of the number of access terminals over time. Therefore, this article proposes a method for estimating the period of terminal upload data and an RTRS algorithm based on the characteristics of the IEEE802.11ah MAC protocol. The RTRS algorithm is divided into two parts, namely the terminal upload data cycle prediction and the RAW packet parameter optimization. In the terminal upload data cycle prediction, the AP uses the proportional integral derivative (PID) method to adaptively track the change in the terminal upload cycle according to the time interval of each terminal to upload data and predict the data transmission cycle. In RAW packet parameter optimization, the AP estimates the number of terminals that will upload data in the next data upload period based on the predicted data transmission time period of each terminal, finds the RAW parameters with the best energy efficiency, and informs the access terminal to follow Optimal parameter access. The simulation results show that, compared with the random channel access algorithm, the success rate of the terminal access channel of the RTRS algorithm is 100%.

2. IEEE 802.11ah MAC protocol

In December 2016, the IEEE released the IEEE 802.11ah protocol standard for IoT applications. The standard works in the frequency band below 1 GHz. In industrial scenarios, it can overcome the electromagnetic interference of industrial machinery and equipment to a certain extent. At the same time, compared with the traditional 2.4 GHz and 5 GHz Wi-Fi protocols, the IEEE 802.11ah has more communication distance (up to 1 km theoretically). In addition, for IoT scenarios, the IEEE 802.11ah enhances the MAC layer and physical layer which supports battery power supply for 3 to 5 years. It supports up to 8191 nodes to access, and allows transmission rate selection from 150 kbit/s to 78 Mbit/s. It is suitable for various types of transmission services and has strong scalability for industrial IoT applications.

The topology of the IEEE 802.11ah standard is a star structure, and all terminals communicate directly with the AP. In the terminal access channel stage, the RAW mechanism means that the terminals are divided into different groups, and it is stipulated that only terminals in one group are allowed to compete for the channel within a certain period of time, thereby reducing the collision probability of channel applications and increasing the data communication throughput rate.

The principle of RAW is shown in Figure 1. AP periodically broadcasts the target beacon transmission time (TBTT) of the beacon, and there are multiple RAW packets between two Beacon frame signals. The terminal wakes up periodically to receive Beacon information, which includes the Beacon time interval and the RAW window parameter setting (RPS) between the two Beacons. RPS contains one or more RAW parameter settings between two Beacon frames, including the RAW start time, RAW number, channel access slot allocation in the RAW group, and the allowed terminal AID range. There are one or more channel access time slots in a RAW group.

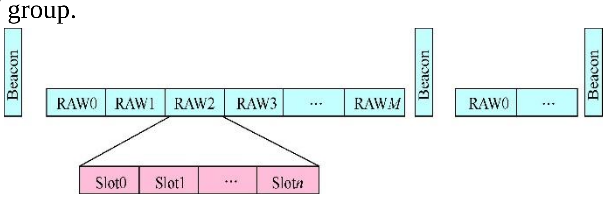

Figure 1. Principle of RAW for beacon transmission

The terminals in the RAW group use EDCA or distributed coordination (DCF) to compete for channels. If the terminal does not belong to the current RAW packet, even if the terminal has data to upload or receive, it will not participate in channel competition, but will be in a dormant state. Using this mechanism can ensure that a large number of terminals stay in a sleep state for a long time and achieve the purpose of reducing system power consumption.

In IEEE 802.11ah, when the backoff value of the terminal decreases to 0, the terminal uploads a PS-poll to the AP to request access to the channel.

After the terminal successfully receives the AP's permission to access feedback, it continues to upload data packets and waits to receive ACK. If the backoff values of two or more terminals decrease to 0 at the same time, a channel conflict will occur between the terminals. After the collision, the terminal enters the back-off state and waits for access to the channel again. At the same time, in order to save energy, IEEE 802.11ah supports a virtual network allocation vector (NAV) mechanism. When the terminal detects that the terminal uploads data, it directly enters the sleep state. From the above analysis, it can be seen that terminal energy consumption mainly includes the following four aspects.

1) The energy consumed by all terminals periodically waking up to receive Beacon broadcast information;

2) During the backoff process, the terminal monitors the energy consumed by the busy and idle state of the channel;

3) The energy consumed by the terminal successfully sending a data flow to the AP;

4) When a conflict occurs, the terminal sends the PS-poll signal and receives the energy consumed by the AP feedback.

3. Proposed Algorithm

3.1 Terminal Upload Cycle Prediction Algorithm

The terminal upload cycle prediction algorithm requires the AP to predict the data upload cycle of each terminal and the list of terminals that need to upload data in the next Beacon cycle based on the terminals that upload data in the current cycle.

For the sake of generality, assuming that a large number of terminals request access to the network to upload data at a certain time interval, the shortest upload time interval for each terminal is not less than 5 upload cycles. In order to track the increase or decrease of the period of data uploaded by the terminal, a dynamic prediction algorithm based on proportional integral derivative (PID) is proposed.

The dynamic prediction algorithm counts the number of times that the AP continuously predicts the upload cycle of the terminal, and obtains the accumulated error for multiple consecutive times. Use the error value to adjust the forecast terminal upload cycle proportionally and integrally; by counting the number of AP consecutive failures to predict the terminal upload cycle, the change trend of the forecast value is obtained; the error change trend is used to quickly adjust the forecast terminal upload cycle to achieve differential adjustment. When the error between the predicted value and the actual transmission period of the terminal is small, the proportional and integral adjustment algorithm implements the main prediction function; when the predicted value and the actual transmission period error of the terminal is large, the differential adjustment algorithm implements the main prediction function.

Let n_{succ}, n_{fail}, and n_{over} be the number of times that the AP continuously predicts the terminal upload period, the number of times that the AP continuously fails to predict the terminal upload period, and the number of times that the AP continuously predicts that the terminal upload period is too large. According to whether the terminal is in the upload queue predicted by the AP in the current Beacon cycle, the implementation process of the terminal upload cycle prediction algorithm is designed as follows.

1) In the current Beacon period, the terminal s is in the upload queue predicted by the AP. If the terminal s uploads data in the current Beacon period, add 1 to n_{succ}. If the terminal s does not upload data in the current Beacon cycle, the processing is as follows.
   a) When the terminal fails to upload data for the first time, it indicates that the estimated upload period $\hat{t}_{\text{int}}^{s}$ is less than the actual interval t_{int}^{s}, and the predicted upload period is increased by $1/n_{\text{succ}}$ period.
   b) When the terminal fails to upload data in the estimated Beacon for several consecutive times, it indicates that the estimated $\hat{t}_{\text{int}}^{s}$ has a large deviation from the actual terminal interval t_{int}^{s}. For each failure, the number of failures n_{fail} is increased by 1, and the estimated upload interval is increased by $2(n_{\text{fail}}-1)+1$.
2) In the current Beacon cycle, the terminal s is not in the upload queue predicted by the AP. When the terminal uploads data in advance for the first time, it indicates that the estimated $\hat{t}_{\text{int}}^{s}$ is slightly larger than the terminal's actual interval t_{int}^{s}, which reduces the predicted upload period by $1/n_{\text{succ}}$ period.

When the terminal uploads data in advance several times in a row, the estimated time t_{int}^{s} changes faster, and it approaches the actual interval $\hat{t}_{\text{int}}^{s}$ of the terminal more quickly. For each advance, the number of advances n_{over} is increased by 1. Set the forecast upload data cycle to $\max\{t_{\text{int}}^{s}-2(n_{\text{over}}-1)+1,1\}$.
The prediction algorithm flow of each node terminal data upload period is shown in Figure 2.

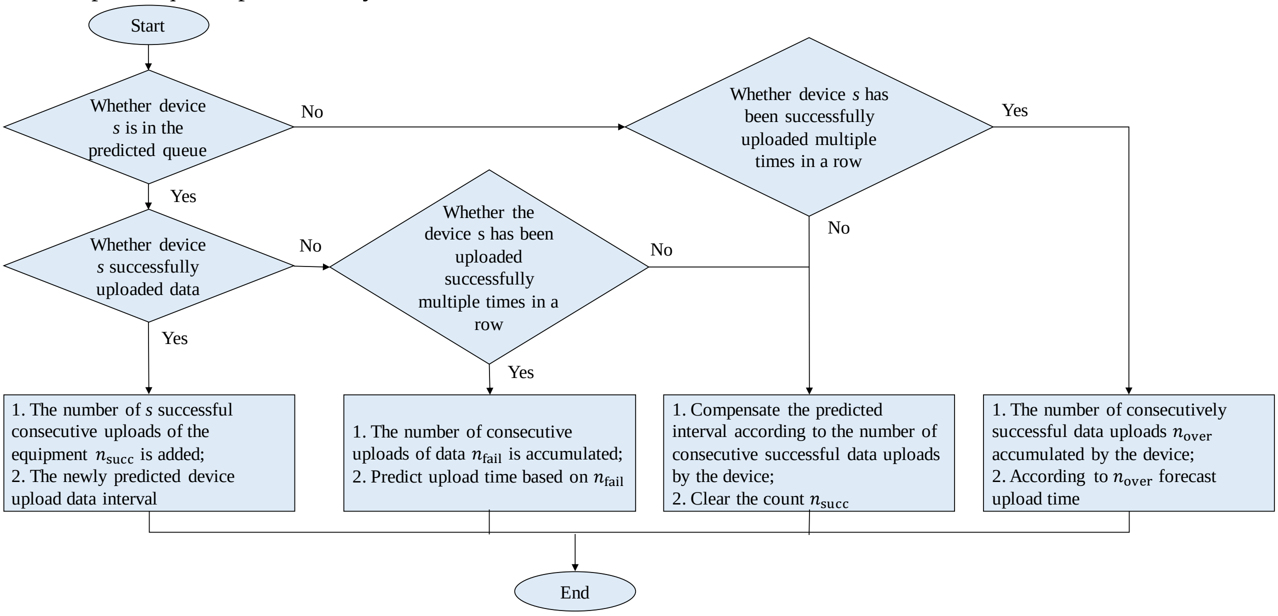

Figure 2. Proposed algorithm flowchart

3.2 RAW Parameter Optimization

3.2.1 Terminal Energy Consumption Analysis

Assuming that there are n terminals competing for the channel in each RAW group, if the backoff value of a terminal in the current time slot decreases to 0, the probability of initiating channel access is

$$\tau=\frac{2(1-2p_n)}{(1-2p_n)(CW_{\min}+1)+p_nCW_{\min}(1-(2p_n)^m)} \tag{1}$$

Among them, p_n is the probability of collision in the current time slot, expressed as $p_n=1-(1-\tau)^{n-1}$.

Any back-off time slot can be divided into three states: successful access, idle, and conflict. According to equation (1), the probability of a terminal successfully accessing the channel in the current time slot is

$$p_{ns}=n\tau(1-\tau)^{n-1} \tag{2}$$

The probability that the current time slot is idle is

$$p_{ni}=(1-\tau)^n \tag{3}$$

The probability of collision in the current backoff slot is

$$\begin{aligned}p_{nc}&=1-p_{ns}-p_{ni}\\&=1-n\tau(1-\tau)^{n-1}-(1-\tau)^n\end{aligned} \tag{4}$$

If a terminal successfully uploads data to the AP, the number of backoff slots that need to pass is $N_n=1/p_{ns}$. Therefore, the total time required for a terminal to successfully upload data to the AP is expected to be

$$T_{ns}=\frac{1}{p_{ns}}T_{\text{slot}}+p_{nc}\frac{1}{p_{ns}}T_c+T_s \tag{5}$$

Among them, T_{slot} is the length of a time slot, T_c is the time consumed by terminal conflicts, and T_s is the time used by the terminal to successfully send data.

When a conflict occurs, at least two terminals simultaneously select the time slot for data transmission. When there are n terminals competing for the channel, the average number of terminals conflicting each time is

$$N_{nc}=\sum_{k=2}^{n}k\tau^k(1-\tau)^{n-k} \tag{6}$$

Therefore, when there are n terminals competing for the channel and one terminal successfully uploads data, the total energy consumed by the terminals in the RAW group is expected to be

$$W_n=nN_nW_r+N_np_{nc}N_{nc}W_c+W_s \tag{7}$$

Among them, W_r is the power consumed by the terminal receiving in a time slot, W_c is the power consumed by a terminal when a conflict occurs, and W_s is the energy consumed by the process of a terminal successfully sending data.

3.2.2 RAW Total Energy Consumption Analysis

According to the characteristics of the low-power Internet of Things, it is assumed that each terminal has at most one data packet to upload in a Beacon cycle. Therefore, in a RAW group, the terminal enters the dormant state after successfully uploading data, and the remaining terminals continue to compete for the channel until all the terminal data is successfully uploaded or the RAW grouping ends. Accumulate the total energy consumed by each terminal for sending successful data to obtain the total energy consumed by the terminal in a RAW group and the total time.

Assuming that there are initially N users in a RAW group that need to be accessed, the number of users who can successfully access is expected to meet the condition of equation (8) as

$$\sum_{k=N}^{T_N} T_{ks} \leq T_{\text{RAW}} \leq \sum_{k=N}^{k=T_N+1} T_{ks} \tag{8}$$

Correspondingly, the energy consumption of T_N terminals successfully sending data is expected to be

$$W_{\text{RAW}} = \sum_{k=N}^{T_N} W_k \tag{9}$$

During system operation, the terminal needs to wake up periodically to receive and analyze the Beacon information broadcast by the AP. Assuming that the Beacon cycle is divided into M RAW packets, the energy consumed by all terminals receiving RPS is

$$W_{oh} = MT_{\text{RPS}}N_{\text{all}}P_{Tx} \tag{10}$$

Among them, M is the number of RAW packets in the system, and T_{RPS} is the time required for one RPS information transmission. In a Beacon cycle containing M RAW packets, when N_{sum} terminals need to upload data to the AP, the total energy that needs to be consumed is sum RAW $W_{\text{sum}} = MW_{\text{RAW}} + W_{oh}$.

Given the number of users in each RAW packet, the number of successfully sent messages can be known, and the amount of information that can be transmitted per unit of energy, that is, the energy efficiency is

$$\eta = \frac{MT_{N_{\text{sum}}/N}}{W_{\text{sum}}} = \frac{MT_{N_{\text{sum}}/N}}{MW_{\text{RAW}}+W_{oh}} \tag{11}$$

3.2.3 Energy Optimal RAW Grouping

It can be seen from equation (11) that when the number of access channel terminals is fixed, if the number of RAW groups is too small, the probability of channel conflicts of terminals in the RAW group is higher, and the energy efficiency is lower. If there are too many groups, there are fewer terminals in the RAW group, and the probability of channel conflicts in the group is low. However, too many groups M will increase the energy consumption of receiving Beacon signals and reduce energy efficiency. Therefore, as the number of groups increases, the energy efficiency of the system first increases and then decreases. There is an optimal number of groups M, which makes the energy efficiency of the system the highest. The optimization equation can be written as

$$\max \eta \tag{12}$$

Subject to:

$$T_{\text{beacon}} - M(T_{\text{RAW}} + T_{\text{RPS}}) \geq 0 \tag{13}$$

Among them, T_{beacon} is the time length of the current Beacon cycle.

Since equation (12) contains iterations of the number of users, it is a nonlinear optimization problem. Therefore, for a given number of users N_{sum}, this paper uses a binary search to find the optimal number of groups M_{opt}, which makes the system energy efficient.

4. Simulation Results

4.1 Simulation Parameters

Assuming that the system has been initialized, each terminal has a specific AID number, and there will be no hidden nodes in the terminal within a certain continuous AID number range. The simulation parameters of the RTRS algorithm are shown in Table 1.

Table 1. Simulation Parameters

Parameter	Value
Communication rate	100 kbit/s
Backoff slot	52 µs
DIFS	200 µs
SIFS	160 µs
Transmit power	200 mW
Beacon cycle	93.6 s
ACK packet size	8 Bytes
Carrier frequency	900 MHz
Maximum competition window	1024
Minimum competition window	8
Maximum number of backoffs	8
Received power	200 mW
RPS parameter size	12 Bytes
PS-poll	16 Bytes

This article simulates from three aspects: 1) the success rate of the RTRS algorithm in the terminal sending data in a data upload period; 2) the influence of the data packet size on the number of optimal system packets; 3) AP predicts the number of terminals that need to upload data The influence of the number on the energy efficiency of the system. In the system initialization phase, the AP's data upload cycle value for each terminal has not stabilized yet, and there are large fluctuations, making the system work for 10 beacon cycles. When the estimated value stabilizes, data statistics will be performed.

In order to prevent the influence of individual experimental results on the system results, after each parameter setting, 100 Beacon cycles are collected to eliminate the influence of random events on the experimental results.

4.2 Simulation Results

4.2.1 Comparison of Terminal Upload Success Rate

In a Beacon cycle, there are 1,000 terminals that need to upload data, and the size of each uploaded data packet is 920 bits. The success rate of terminals uploading data with different algorithms is shown in Figure 3. It can be found from Figure 3 that when the number of RAW packets is not less than 5, the terminal upload data success rate in the RTRS algorithm approaches 100%; when the random time slot selection algorithm is 1-20, the terminal uploads The data success rate has always been maintained at around 85%. The random selection of access time slots will result in a lot of waste of access time slots, which reduces the overall data upload success rate of the system. When using the RTRS algorithm, if the number of RAW packets is small, the success rate of the terminal uploading data will be low. As the number of packets increases, the number of terminals in the RAW group gradually decreases, the channel busyness decreases, and the success rate of terminal uploading data gradually increases until there is no packet loss.

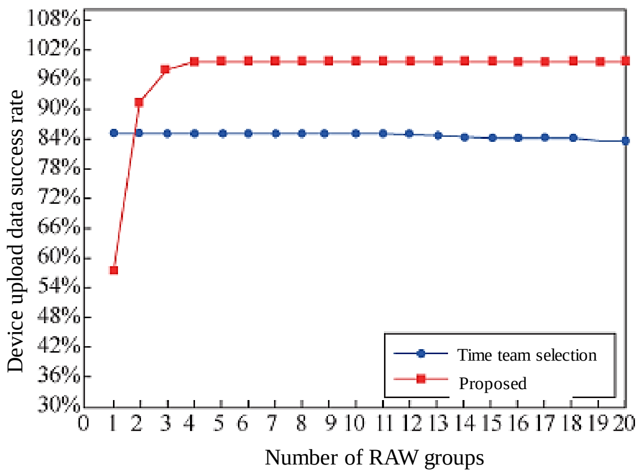

Figure 3. Success rate of uploading data from different algorithms

4.2.2 The Impact of Terminal Data Packet Size on the System

The impact of data packet size on system performance is shown in Figure 4. From Figure 4, it can be found that when the number of packets is the same, the larger the data packet uploaded by the terminal each time, the higher the corresponding system energy efficiency. Because when the terminal uploads data to the AP, other terminals are in a dormant state and do not need to consume additional energy. The larger the data packet sent by the terminal, the larger the proportion of the corresponding useful power consumed. Therefore, the larger the data packet uploaded by the terminal, the higher the corresponding system energy efficiency.

At the same time, it can be seen from Figure 4 that the size of the data packet uploaded by the terminal does not affect the number of RAW packets when the system energy efficiency is the highest. When the number of access terminals is about 1,000, the optimal grouping range of RAW is (12,16). When the number of terminals accessing the system in the Beacon period is certain, the number of RAW groups determines the busyness of the channels in each RAW group. When the number of terminals connected to the system and the upload data packet size are fixed in each cycle, the optimal RAW packet number range can be obtained.

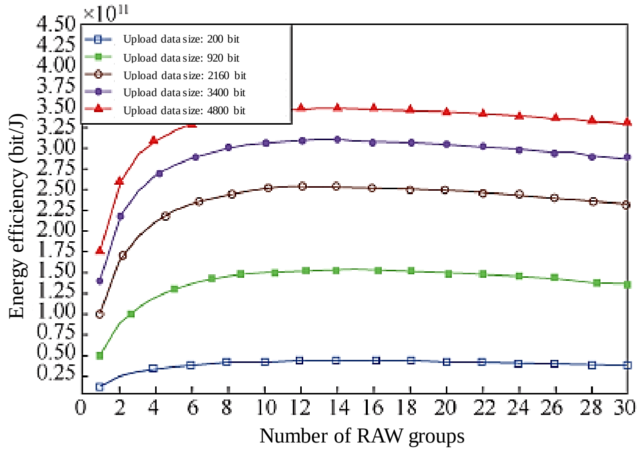

Figure 4. The Impact of Data Packet Size on the energy efficiency

4.2.3 The Influence of the Number of Access Terminals on the System

The impact of the total number of terminals on system performance is shown in Figure 5. As the number of RAW groups increases, each energy efficiency curve shows a trend of rising first and then falling. When the number of RAW groups is small, there are more terminals in the RAW group, and channel competition and conflict are serious, resulting in lower overall energy efficiency of the system. When the number of RAW packets increases, the channel competition and conflict situation among terminals in the RAW group is eased, and the system energy efficiency increases; when the number of packets is too high, all terminals need to consume more energy to receive the RAW packet setting signaling RPS.

For different numbers of access terminals, the optimal number of RAW packets is different. When the number of access terminals is 1,000, the optimal RAW partition number range is (12,16), when the total number of access terminals is 5,000, the optimal RAW partition number range is (23,28). The optimal number of RAW divisions increases as the number of access terminals increases. When the number of RAW divisions is fixed, as the number of access terminals increases, the competition and conflict of terminals in the RAW group will increase, and the number of RAW groups needs to be increased. To reduce the probability of terminal competition conflicts in the RAW group, thereby improving energy efficiency.

According to the above analysis, in a Beacon cycle, when the number of terminals connected to the system is fixed, the upload data packet size within a certain range does not affect the number of RAW optimized packets. The range of the optimal number of RAW groups is affected by the number of terminals connected to the system. According to this feature, when the AP estimates the terminal queues that need to upload data in the next Beacon cycle, the optimal number of RAW divisions can be obtained The range of energy efficiency of the system is optimized in real time.

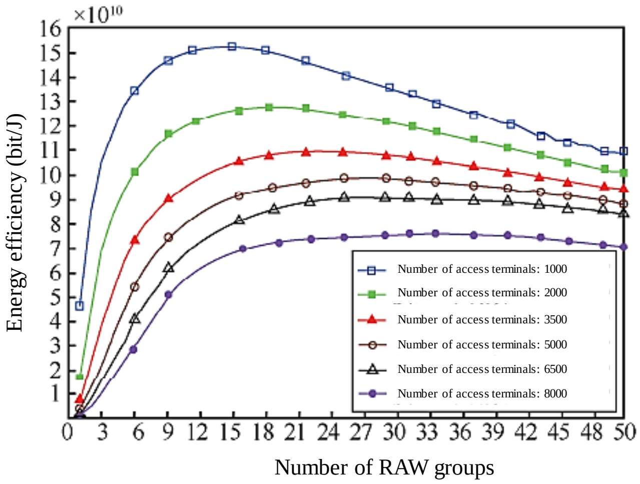

Figure 5. The impact of the total number of terminals on system energy efficiency

5. Conclusions

This article aims at low power consumption in IoT communication and proposes RTRS algorithm based on the IEEE 802.11ah standard to realize dynamic user number estimation during system communication and dynamically adjust RAW packet parameters in real time to achieve the goal of the highest system energy efficiency. Theoretical analysis for beacon timeframe and other important factors were derived. Simulation results indicated that the proposed algorithm effectively improved the system performance in terms of data packet rate, success rate and number of access terminals. Further research as an extension to this work is to consider the quality-of-service analysis in terms of throughput, bit error rate and SINR.

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