Energy-aware Adaptive Restricted Access Window for IEEE 802.11ah Based Smart Grid Networks

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Abstract—Restricted Access Window (RAW) has been introduced to IEEE 802.11ah MAC layer for application of smart grid networks to decrease collision probability. The number of devices involved and duration affect both transmission energy and overhead information. However, few work has been done on energy efficient RAW. In this paper, we investigate an energy efficient RAW optimization problem for IEEE 802.11ah based uplink communications. We first formulate the problem based on overall energy consumption and the data rate of each RAW by applying probability theory. Then, we derive the energy efficiency of the uplink transmission. Last but not the least, an access window algorithm to adapt the RAW size is proposed to optimise the energy efficiency by identifying the number of contending devices and the number of slots in each RAW. Simulation results show that our proposed algorithm outperforms existing RAW on uplink energy efficiency.

I. INTRODUCTION

Tomorrow smart system brings in scalable services based on self-control system, which is done by efficient management of utilities. Smart grid provides intelligent transfer and usage of power and energy, indicating there will be a large number of sensors and devices [1] [2]. So robust information and communication technologies play a significant role for constructing such networks [3]. However, existing wireless technology, such as RFID, ZigBee, Bluetooth, etc., can not accommodate this amount of devices with high throughput over a large transmission range [4].

Fig. 1. Smart grid infrastructure applied IEEE 802.11ah.

One of the latest wireless communication technologies that have been proposed for smart grid application is the Low Power Wi-Fi [2], as shown in Fig. 1. IEEE 802.11ah Wireless LAN standard group has put forward IEEE 802.11ah to support Low Power Wi-Fi, which started in November 2010 and is expected to finish not before January 2016 [5]. IEEE 802.11ah operates at sub-1 GHz and it can support up to 6000 devices within a network with transmission range up to 1 km at the rate of more than 100 kbps [6]. Restricted Access Window (RAW) is a new MAC layer feature that used in Low Power Wi-Fi to decrease collision. It limits a set of devices that can access the channel at any time and spreads their attempts over a long period of time [5] [7]. RAW consists of multiple equal time slots, where each slot is selected by devices or assigned to a group of devices for transmission [4] [8]. Devices are in wake-up mode only when turning to their RAW, otherwise would be in doze mode.

There is no standard definition for RAW duration and the amount of devices which could contend simultaneously, which both affect the energy efficiency. When duration of one RAW is long, the devices involved should be in active mode for a longer period, leading to expending idle wake-up energy. On the contrary, the collision probability would be high if a large number of devices access through RAW with limited time slots, resulting in low efficiency. And RAW has a effect on overhead information to inform scheduling information. Thus appropriate number of devices in adaptive RAW duration could reduce low energy consumption and achieve a high data rate.

The way to improve energy efficiency has been studied in depth in many research works, mainly focus on improving successful transmission probability and reducing collision. In [8], a new medium access control enhancement algorithm was proposed to calculate optimal size of RAW. It used Maximum Likelihood (ML) estimation method to estimate the number devices for uplink access and determine the optimal size of RAW. However, it only calculated according to successful transmission probability without consideration of energy. In [9], the authors introduced Successive Interference Cancellation to improve the throughput in limited time but this could result in more collisions. In [10] and [11], new algorithms were proposed to calculate wake-up time of devices. They used probability theory and matrix way, which could monitor different communication scenarios, to build analysis model. However, these algorithms have not embodied the RAW communication mechanism. In [12], low collision probability was achieved through access control to limit the number of devices contending by setting the threshold of access point (AP), and making a decision by comparing threshold with the numbers that devices generate in the network. It only fitted for authentication stage instead of transmitting and receiving process.

The aforementioned literatures laid a solid foundation in improving energy efficiency based on transmission probability and reducing collision for IEEE 802.11ah. Less work
has been done to optimise the energy efficiency with joint consideration of RAW size and clustering size. To address the above joint consideration, in this paper we study an optimisation problem aiming at maximizing uplink energy efficiency through RAW. An access window algorithm is proposed to determine the number of devices contending simultaneously as well as RAW duration for uplink communications. An optimal solution is derived by Simulated Annealing, a generic probabilistic metaheuristic for the global optimization problem.

The remainder of the paper is organised as follow. Section II describes system model about IEEE 802.11ah MAC protocol. Problem formulation is given in Section III. Section IV presents the derivation of optimal solution. Section V provides the simulation results to show the efficacy of algorithm we proposed. Finally, section VI concludes the paper.

II. SYSTEM MODEL

We consider a single-hop topology for dense IEEE 802.11ah smart grid networks as a single Access Point (AP) with a high number of devices. RAW groups the devices and splits the channel into equal time slots [13], as shown in Fig. 2. All devices in this network listen in the beginning of beacon frame called Target Beacon Transmission Time (TBTT) to obtain scheduling information that indicates which RAW they belongs to. Then devices would fall into sleep mode until turning to their RAW to attempt accessing. For each RAW, there are M time slots and N devices limited by lowest and highest Associated Identifier (AID) of devices which indicate the location, traffic, type, energy saving mode etc [4].

![RAW structure](Fig. 2. RAW structure.)

In uplink communications, the devices that have buffered data for the AP select a time slot of their RAW randomly and attempt to access channel as shown in Fig. 3. If there is only one device in a slot, it could access directly as Device 1 transmits packet in Slot 2 directly without contention as well as Devices 3 in Slot M. When there are more than one device choosing the same time slot as Device 2, Device 4 and Device N all select Slot 4, they would come into the back-off stage to avoid collision by doubling contention window and trying again until coming to the slot boundary. If accessing successfully, device requests uplink communication by sending PS-poll message to the AP. AP responses with an ACK to confirm connection. After the first handshake, the device transmits buffered data frame and waits for ACK from AP [14]. Due to focusing on MAC layer, we assume that packets are always transmitted without transmission error due to the channel impairments. The process is repeated, one RAW by one RAW, until coming to the end of beacon frame.

![Operation of RAW](Fig. 3. Operation of RAW.)

Due to random selection, as for a time slot in RAW, the probability that there are i devices to choose is

$$P(i) = \binom{N}{i} \left( \frac{1}{M} \right)^i \left( 1 - \frac{1}{M} \right)^{N-i},$$

where M is the number of time slots contained in one RAW, which indicates the duration of one RAW; N is the number of devices that could be involved in one RAW intending to access channel, showing RAW capability. So the probability of more than one device to choose the same slot is

$$P_{>1} = \sum_{i=2}^{N} P(i).$$

For a single device, it could choose any time slot in its RAW. The probability of the time slot one device chooses only containing itself (Case 1) is

$$P_1 = \left( 1 - \frac{1}{M} \right)^{N-1}.$$  

So if one device buffers an uplink packet every time for \(\mu\) communications, there would be \(\mu P_1\) packets being
transmitted directly by occupying a time slot by itself.

For Case 2, the time slot one device chooses contains \((i-1)\) other devices to contend. The probability of this device building connection with AP in minimum contention window as first back-off stage is

\[
P_{\text{back-off}}(i) = \frac{1}{W_{\text{min}}} \sum_{k=0}^{W_{\text{min}}-1} \prod_{n=0}^{k-1} \left[ 1 - \frac{1}{W_{\text{min}}} \left(1 - \frac{k}{W_{\text{min}}} \right)^{i-1} \right] \frac{1}{W_{\text{min}}} \left(1 - \frac{k+1}{W_{\text{min}}} \right)^{i-1}
\]

(3)

where \(W_{\text{min}}\) is the minimal size of contention window.

Although there are \(i\) devices selecting the same time slot in one RAW, a device could access the channel and communicate with AP is based on the probability as follows

\[
P_2(i) = P(i)P_{\text{back-off}}(i),
\]

(4)

where \(i\) is from 2 to \(N\).

Thus as Case 2, the overall probability for one device needing to contend in the time slot it choose and accessing channel successfully is

\[
P_2,\text{alt} = \sum_{i=2}^{N} P_2(i).
\]

(5)

The successful transmission probability for one device to transmit one packet is the sum of two cases, which could be denoted by

\[
P = P_1 + P_2,\text{alt}.
\]

(6)

Based on different states a device may fall into with various probability, the energy consumption of one device to transmit single packet in one RAW is

\[
E = P_1E_{s1} + P_2,\text{alt}E_{s2} + (1-P)E_c + ME_{\text{con}},
\]

(7)

where \(E_{s1}\) is the energy consumption when transmitting a packet successfully as Case 1; \(E_{s2}\) is the amount of energy consumed if transmitting successfully in Case 2; \(E_c\) is the energy waste when there is collision so that it needs to retransmit in another RAW; \(E_{\text{con}}\) is the contention power in one RAW, which is the energy consumed when it is in wake-up mode.

The size of RAW also determines the energy consumption of transmitting overhead information, because when the window duration is too small, the overhead information of each device would be high due to the scheduling information that needs to be transmitted multiple times in a short time. And if the number of devices involved in one RAW is small, it also needs massive scheduling information to realize network communication. So the energy consumption of head information is related to \(N\) and \(M\):

\[
E_{\text{head}} = \frac{\alpha}{M} \times \frac{\beta}{N},
\]

(8)

\(\alpha\) is the parameter indicating traffic and \(\beta\) is the parameter related to overall number of devices in the scenario.

Energy efficiency of one RAW could be evaluated by the data rate it provides and overall energy consumption including transmitting or collision energy and overhead energy. Data rate could be formulated as

\[
R = \frac{N \times P \times \gamma}{\delta M},
\]

(9)

where \(\gamma\) is the packet size and \(\delta\) is the time duration of one time slot. \(N \times P \times \gamma\) is the total length of packets could be transmitted for \(N\) devices in \(M\) time slots. \(\delta M\) is the total time of one RAW.

The overall energy consumption consists of transition power and overhead power when \(N\) devices attempt to communicate with AP during one RAW, which could be denoted by

\[
E_{\text{overall}} = N(E + E_{\text{head}}).
\]

(10)

Thus energy efficiency is

\[
EE(M, N) = \frac{R}{E_{\text{overall}}} = \frac{\gamma P}{\delta M(E + E_{\text{head}})}.
\]

(11)

With \(P\), \(E\) and \(E_{\text{head}}\) being built by \(M\) and \(N\), energy efficiency is a function related to the number of devices involved and time slot in one RAW. We could maximize energy efficiency by finding optimal \(M\) and \(N\).

IV. ENERGY EFFICIENT RAW

We formulate the main part of energy efficiency \(f(M, N)\) along with the various number of devices that could be involved per RAW \(N\) and the amount of time slots in one RAW \(M\) on Matlab, denoted by

\[
f(M, N) = \frac{P}{M(E + E_{\text{head}})}.
\]

(12)

According to the result as shown in Fig. 4, \(f(M, N)\) is a concave surface with peak value, at which point network would perform better with the same energy consumption. Due to the collision probability being relative high with small \(M\) and large \(N\), the optimal value should be chosen near the centre of Fig. 4.

Fig. 4. Main part of energy efficiency, \(f(M, N)\).

We find optimal set of number of devices and RAW duration to maximize energy efficiency by applying Simulated Annealing, an iterative algorithm to find the optimum of large search space as shown in Algorithm 1.
Algorithm 1 Simulated Annealing Access Window Algorithm

1: Step 1: initialize random input set \((M_0, N_0)\) as pre_best_set and another random set \((M_1, N_1)\) as best_set.
2: Step 2: find optimal point.
3: cooling until meet the requirement for iteration
4: \(mm = |EE(M_1, N_1) - EE(M_0, N_0)|\);
5: while \(mm > Tolerance\) do
6: Temperature=\(\text{DecayScale} \times \text{Temperature}\);
7: for \(i\) in the range of 0 to MarkovLength do
8: while do
9: select next input
10: next_set = pre_set + Step;
11: if next_set lies out of input limitation then
12: end the loop
13: end if
14: end while
15: check whether is global optimum
16: if new_EE > best_EE then
17: reserve previous optimum
18: end if
19: Metropolis process
20: if pre_EE < next_EE then
21: accept this point and start next iteration based on this point;
22: else
23: changer=(next_EE-pre_EE)/Temperature;
24: if exp(changer) > rand, do not accept new solution.
25: end if
26: end for
27: \(mm = |EE(\text{best_set}) - EE(\text{pre_best_set})|\);
28: end while
29: return best_set;

This algorithm is a standard Simulated Annealing approach to find the optimal solution. It starts with an arbitrary value based on a random set, and then compare the existing optimum with a new function results with input that adding a step. When upcoming one performs better, accept new one, otherwise, reserve previous. If the gap is larger than tolerance, cool one time and decrease temperature until annealing. The times loop will go is according to Markov length.

V. SIMULATION RESULT AND ANALYSIS

In this section, the optimization algorithm for RAW is evaluated in Matlab. We consider a one-hop topology as describe in the system model.

We apply wake-up/sleep mode for all devices. At each RAW, there are \(N\) devices being allocated. When coming to their RAW, devices keep wake-up mode and randomly select their own time slot to do transmission to the AP, otherwise they would fall into sleep mode. We assume every device involved has exactly one packet to transmit for uplink communications during a RAW. The main simulation parameters are given in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency</td>
<td>0.9 GHz</td>
</tr>
<tr>
<td>data rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>transmit power</td>
<td>1.346 mw</td>
</tr>
<tr>
<td>transmit power in back-off stage</td>
<td>2.5 mw</td>
</tr>
<tr>
<td>collision power</td>
<td>3.0 mw</td>
</tr>
<tr>
<td>idle listen power</td>
<td>0.001 mw</td>
</tr>
<tr>
<td>slot duration</td>
<td>31.1 ms</td>
</tr>
<tr>
<td>min contention window</td>
<td>8</td>
</tr>
<tr>
<td>max contention window</td>
<td>1024</td>
</tr>
<tr>
<td>packet length</td>
<td>1024 bits</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>200</td>
</tr>
<tr>
<td>(\beta)</td>
<td>200</td>
</tr>
</tbody>
</table>

Fig. 5. Energy efficiency comparison based on same number of time slots with various amount of devices.

The energy efficiency varying over diverse number of devices based on three different durations of one RAW (\(M=94, 174, 254\)) is shown in Fig. 5. It can be observed that the curves are concave and the optimal duration (\(M=174\)) leads to better performance compared with \(M=94\) and \(M=254\). The peak point is 30250 bits/J at 89 with \(M=174\), which fits the theory analysis result, 9.5% higher than peak of \(M=94\) or 254.

As for the behaviour with optimal RAW size (\(M=174\)), the curve keeps sharp growth with increasing number of devices before 89. The optimum could improve 36% compared with 40 devices. And after peak, the trend is down. Energy efficiency decreases to around 18% if the number of devices reduces from 140 to 89.

When the number of devices is low, energy efficiency of three scenarios have close performance due to the fact that the ratio of time slots and devices is high, resulting in few collisions. However, there are small amount of devices or packets transmitting in one RAW, thus overhead energy dominates.
the energy consumption. With the rising number of devices, as for overview the whole networks, overhead informations do not need to be sent multiple times. It increases 65% for 40 devices involved compared with 20. However, after the peak, the trend declines. And rate of abatement is higher when duration is shorter. With the increase of number of devices, the collision probability would be high which leads to consume more energy and low data rate, two parameters for low efficiency. And it also is the reason that the scenario with fewer time slots for devices selection performs worse due to high number of collisions.

Fig. 6. Energy efficiency comparison based on same number of devices with various amount of time slots.

Fig. 6 shows the energy efficiency with three amounts of devices (N=49, 89, 129) as it varies along diverse number of time slots. The highest point is at M=174, N=89 as we expected. It is obvious that the optimal number of devices involved (N=89) has better energy efficiency, approximately 9% higher for peak point in N=89 compared with the peak in the other two scenarios.

For N=89, the optimal number of time slots is 32% better than M=70, and 12% better than M=290. Although the peak is at M=174, the curve is nearly stable around the peak. Choosing proper amount of devices and RAW duration gives improvement in energy efficiency.

When the RAW duration is short that means the number of time slots is small and the three curves all go up, the rate of which are negatively correlated with the number of devices. At this stage, collision dominates the data rate and energy consumption. So with increasing duration, there are more choices for devices, so fewer collision which improves energy efficiency. That also is the reason that the lowest number of devices has higher efficiency. However, if the RAW duration is too large, due to long time to be wake-up mode, contention power of devices would be high which makes energy efficiency drop. As for N=49, overhead information energy is consumed much more than the other two, so it is the worst one when duration is large.

Fig. 7. Energy efficiency comparison between existing RAW and proposed RAW.

Fig. 7 shows the comparison between existing RAW and the proposed one. The compared existing scheme in [12] selected 100 time slots per RAW. According to Fig. 7, the energy efficiency of existing RAW has a similar trend with the curves in Fig. 5 vs. different number of devices. However, the maximum energy efficiency the existing RAW could achieve is still lower than our proposed RAW set (N=89, M=174). The minimum energy efficiency improvement of the proposed RAW is approximate 7.3% compared to the existing RAW.

Simulation results demonstrate energy efficient RAW with the optimal combination of the number of devices involved and duration of one RAW could bring about superior energy efficiency for IEEE 802.11ah uplink communications.

VI. CONCLUSIONS

In this paper, we focus on energy efficiency for smart grid communications. An channel access window algorithm is proposed for IEEE 802.11ah networks to optimize uplink communications energy efficiency through adapting number of devices access simultaneously in RAW with appropriate duration. The algorithm is built based on probability theory to evaluate transmission probabilities of various states a device may fall into when sending a packet during one RAW. On account of that, overall energy consumption and data rate are estimated to contribute to energy efficiency. To maximize the energy efficiency, we calculate the optimal solution by applying Simulated Annealing. Simulation results demonstrate that the joint optimal RAW duration and number of devices could lead to improvement of energy efficiency for one RAW. Our results show that the dominate factor of energy efficiency various over the number of devices or time slots in one RAW. The primary one is overhead information energy with low amount of devices, and it changes to collision waste when involving a mass of devices. While with extending of RAW duration, the crucial element is from collision waste to wake-up power. The superior energy efficiency is achieved under balanced combination for one
RAW (89 devices with 174 time slots).

REFERENCES


