Enhanced Power Saving Mechanism for Large-Scale 802.11ah Wireless Sensor Networks

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***Abstract*—We consider the power saving mechanism for 802.11ah on large-scale sensor networks. Power saving mode allows sensor nodes to switch to low-power state while APs buffer incoming frames for them. Also, 802.11ah introduced TIM and page segmentation scheme to cope with a large number of nodes. Although it is a powerful tool for reducing contention and increasing sleep intervals, the advantage comes at the expense of additional energy waste, which becomes exacerbated as the number of nodes increases. This paper aims at minimizing such energy waste and enhancing energy efficiency which is critical to large-scale 802.11ah networks. We propose a method that selectively and dynamically changes the membership of nodes and rearranges their traffic to maximize overall sleeping intervals without causing delay to data delivery. To this end, we propose a temporary membership change scheme and a traffic scheduling algorithm which reduce overall power consumption. Also, to make the problem tractable and scalable, we apply a relaxation technique and devise a low-complex scheduling algorithm, respectively, of which performance is comparable to optimum. Evaluation results show that the proposed scheme can enhance energy efficiency by decreasing the number of active nodes by up to 37.8% compared to 802.11ah.**

***Index Terms*—802.11ah, large-scale wireless sensor networks, power saving mechanism.**

I. INTRODUCTION

ALONG with the continuous development of the communication devices and networking technology, the idea which is to connect physical wireless sensor nodes located at the surrounding area and thus, to provide a diverse range of applications has received much attention. Among various techniques in connecting a large number of devices to the Internet, IoT[1] has recently drawn attention from academia and industry, although it was first introduced back in 1998 [4]. IoT is expected to play a remarkable part in many applications, such as environmental monitoring, smart building, health care, home automation, disaster alerting and ambient assisted living [4] [6] [10], to name a few. Also, its potential for practical use has been shown in many literatures, including IoT testbeds [2] and the off-the-shelf market products [3].

One of the major technical challenges in realizing IoT applications is an absence of unified communication technology for sensor nodes. Therefore, different applications have been using different networking systems to connect devices (e.g., Zigbee, 802.15.4, 6LoWPAN, Bluetooth, cellular networks, etc. [7]) for their own good or specific missions [1]. To this end, IEEE 802.11ah Task Group was formed in 2010 aiming at providing a unified solution for connecting and integrating a large number of (possibly heterogenous) battery-powered devices at the license-exempt band below 1 GHz, excluding the TV White Space bands.

Table I
ABBREVIATIONS AND ACRONYMS

AID	Association Identifier
AP	Access Point
DL/UL	Downlink/uplink
(D)TIM	(Delivery) Traffic Indication Map
IoT	Internet of Things
MAC	Medium Access Control
RAW	Restricted Access Window
STA	Station, i.e., (sensor) node/device
TIM STA	a STA that shows its paged status in TIM

Although a part of the specification [5] is inherited from the previous IEEE 802.11 standards, e.g., 11n and 11ac, a long transmission range (~1km), supporting a large number of STAs (up to ~8,000), coexistence/integration with 802.15.4 devices, and an enhanced power saving are the ones that uniquely distinguish 802.11ah from the rest of the IEEE 802.11 family; interested readers can refer to [8] and [9] for system requirements and use cases, respectively. In other words, unlike the previous 802.11 standards that are designed to provide high data rates for small-/medium-sized networks, 802.11ah is intended to handle a large number of battery-limited STAs per AP with a low data rate [10] and a large coverage for an extended lifetime, which is why energy efficiency has to be one of the primary concerns.

As expected, 802.11ah inherited the power saving mechanism from its predecessors to prolong the lifetime of STAs. In addition, *TIM and page segmentation*, combined with a restricted access mechanism, is introduced to efficiently cope with a large number of STAs; to be specific, STAs are clustered into multiple groups, and each of which is assigned a dedicated time interval for channel access. By efficiently limiting the level of contention, STAs can spend less time on channel access and more in low-power state. For a STA to retrieve buffered data from AP, it periodically wakes up to receive DTIM, which is a group-wise paging status, and if paged, it wakes up on their assigned time interval to listen to TIM, which is a STA-wise paging status. In spite of its advantage, however, the paging-based power saving mechanism causes an unnecessary energy waste problem. A STA that does not have any buffered data has to wake up if the group to which

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[1] Abbreviations and acronyms that frequently appear in this paper are summarized in Table I.

the STA belongs is paged, and the energy waste from such unnecessary wake-ups becomes exacerbated as the number of STAs increases.

Previous studies concerning power consumption [21] [23] [26] have focused on the energy efficiency mainly in regard to the channel access. This approach can be beneficial if STAs are backlogged and actively trying to access the channel for most of the time, but that is not likely to be the case, in general, for 802.11ah sensor networks [7] [9] [10]. Rather, maximizing both the number of sleeping STAs and their sleep intervals needs to be a top priority to enhance energy efficiency for a large-scale sensor network with low traffic rate. It has not been noticed that, as the number of STAs increases, 802.11ah power saving and paging scheme might cause a frequent, unnecessary energy waste for the aforementioned reason, which is the motivation of this paper. In this regard, our goal is to identify and address the unnecessary energy waste problem of 802.11ah power saving mechanism. To this end, we propose a novel solution that maximizes the overall energy efficiency while being compliant with 802.11ah.

In this paper, we propose a dynamic membership change mechanism for a large-scale 802.11ah wireless sensor network to prolong the lifetime of STAs by increasing their sleeping periods. Specifically, the proposed mechanism reduces the number of STAs that have to unnecessarily wake up under the 802.11ah power saving mechanism. To this end, we formulate an optimization problem that establishes an additional membership relation. Its solution provides an optimal strategy that allows some selected STAs to temporarily change their membership such that the following scheduling algorithm can maximize the number of sleeping STAs. Also, we apply a relaxation technique to the optimization problem to make it tractable, while keeping the optimality gap small. What follows is to propose a low-complexity traffic scheduling algorithm that maximizes the sleeping intervals for STAs. Its performance in terms of the number of STAs in low-power mode is comparable to the optimal scheduling scheme, while incurring much less overhead. The proposed idea does not depend on or assume any particular grouping of STAs. Also, it makes use of the same TIM/AID structure as defined in 802.11ah [5] and does not require any significant changes. Thus, the proposed method is compatible with 802.11ah with little modification. Finally, the proposed traffic scheduling algorithm is lightweight, making it suitable for online processing.

The rest of the paper is organized as follows. A brief introduction to IEEE 802.11ah MAC and the motivation of the research is given in Section II. An overview of the previous works is summarized in Section III. The following Section IV introduces the network system model and assumptions. Section V and VI presents the proposed *Secondary AID Assignment* and the *Traffic Scheduling* algorithm, respectively. The evaluation and comparison results are presented in Section VII, and finally, we conclude the paper by Section VIII.

II. PRELIMINARIES

In this section, we first provide a brief introduction to 802.11ah MAC. In what follows, we present an illustrative example scenario that motivated this research.

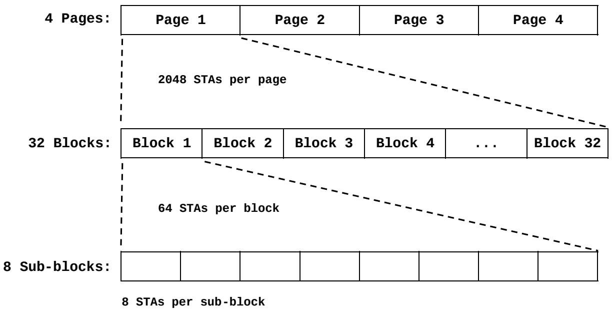

Figure 1. Illustration of the 802.11ah TIM structure.

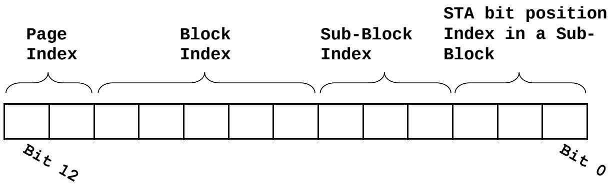

Figure 2. Illustration of the 802.11ah AID structure.

A. 802.11ah MAC: TIM and Page Segmentation

In this study, we focus on the 802.11ah TIM STAs whose *paged* status is included in TIM; interested readers can refer to [5] [7] for the detailed description of the 802.11ah MAC features. The term *paged* in this paper refers to the case that there is at least one data buffered at AP. A STA is paged (by TIM) if an AP has pending traffic for the STA, and in this case, the TIM group to which the STA belongs has to be paged (by DTIM) as well.

TIM and page segmentation have been introduced in 802.11ah to effectively manage a large number of STAs, reduce the level of contention, and enhance the energy efficiency in a structured manner. By limiting the number of STAs that are allowed to participate in contention at the same time, STAs spend less time in channel access and more in low-power state. TIM is structured in a 3-level hierarchy as shown in Fig. 1. Throughout the paper, we assume the same parameters for the number of pages and blocks as in [5]. As shown in Fig. 2, the structure of AID is closely related to that of TIM by having a 3-level hierarchical structure, i.e., page/block/sub-block. A set of STAs whose AIDs are within a certain range belong to the same TIM block (referred to as *group* in this paper), and they are assigned to the same time period during which they are exclusively allowed to access the channel. In addition to the structured TIM/AID as well as the grouping of STAs, both power saving mechanism and page segmentation enable an efficient power and transmission management.

The power saving mode allows STAs to turn off their communication interfaces for a certain period of time to reduce energy consumption and, in the meantime, an AP buffers incoming traffic for them. TIM stations periodically wake up to receive DTIM/TIM, which lets TIM STAs sleep as much as possible and wake up only when they are allowed to contend for the channel. STAs in the same TIM group wake up during their designated time period, and thus their contention is not interfered by the rest TIM groups. Therefore, the level of contention for accessing the channel becomes limited, while the sleeping interval increases. Time is slotted into multiple DTIM intervals, each of which is further divided into multiple TIM intervals. At the beginning of each DTIM interval, all TIM STAs must wake up and listen to DTIM which is a group-wise page status map. However, it does not specify which STA(s) is paged. Therefore, every STA in the paged TIM group needs to wake up on its TIM interval (i.e., the time interval for the group to which the device belongs) to see if it actually has any buffered traffic at the AP; on the other hand, STAs in the non-paged TIM groups remain asleep.

B. Motivation

Although the TIM-based page segmentation scheme has many advantages, it might incur an undesired energy waste for what is called *unnecessary wake-up* in this paper. As aforementioned, STAs in low-power state must wake up to receive DTIM and TIM, if their group is paged. For those STAs that expect frequent traffic arrivals, waking up on their TIM interval is likely to be *necessary*; in other words, it is likely that the AP has buffered data for them. On the other hand, a STA which rarely or occasionally receives traffic will see its wake-up as *unnecessary* in most cases; in other words, it wakes up only because one or more other STAs in the same TIM group is paged, and thus its wake-up will be a waste of energy (i.e., there is no buffered traffic for it). To make matters worse, the unnecessary wake-up problem becomes exacerbated as the number of STAs increases because the probability of a group being paged increases with the aggregate traffic rate of the group. As a result, the energy efficiency of each individual STA as well as that of the entire network is degraded.

Although a few number of such unnecessary wake-up events might consume a negligible amount of power, considering that the expected lifetime of an 802.11ah STA is long (i.e., from months to years [7]) and the number of STAs on the network is large (up to ~8,000), a STA which is frequently exposed to such a case will suffer from a severe energy waste in the long run. For example, let the duration of a single TIM group be 200ms [7] and the number of TIM groups in total is 32, which results in 6.4s of one DTIM interval. Assuming a year of expected lifetime, each STA will encounter approximately 5×10^6 times of DTIM intervals. On each interval, a STA that unnecessarily wakes up will waste σ amount of more energy compared to staying in low-power state. The additional energy waste σ amounts to: $2 \cdot P_{ST} + P_{ACTIVE}(t) + P_{RCV}(t) - P_{SLEEP}(t)$, where P_{ST}, P_{ACTIVE}, P_{RCV} and P_{SLEEP} are the power consumption for making state transition, staying in active state, signal reception and decoding, and staying in sleep state, respectively, and t is the amount of time spent. For each individual STA, the increase in the probability, p, of making unnecessary wake-ups results in wasting approximately $5 \times 10^6 p\sigma$ amount of energy, which is mainly caused by having more STAs in the same group. Obviously, the total amount of energy waste from the entire network significantly increases for the same reason. In order to reduce such unnecessary wake-ups and thus, to increase the energy efficiency, we propose a scheme that enables both a temporary membership change and traffic scheduling. The following example shows how the proposed idea can efficiently achieve the goal without requiring much of the changes to the 802.11ah operation.

Let us assume a simple TIM and AID structure where there is only one page and two TIM groups, and each TIM group can associate with up to 4 STAs. On the network, seven STAs, from n_1 to n_7, are associated and grouped as: $TIM_1 = \{n_1, n_2, n_3\}$ and $TIM_2 = \{n_4, n_5, n_6, n_7\}$. Here, TIM_2 group is fully occupied, while TIM_1 has one unused (AID) slot. Right before the beginning of the i-th DTIM interval, the AP has two buffered data, one for $n_1 \in TIM_1$ and the other for $n_7 \in TIM_2$. Since both TIM groups have at least one pending data for each at the AP, the paged status or block bits (i.e., indication of the presence of the buffered traffic for each TIM group) for both TIM groups need to be set in DTIM. At the beginning of the TIM period for each group, all STAs in the corresponding group must wake up and receive TIM since their group is paged in DTIM. In this simple example, five stations experience unnecessary wake-up events.

On the other hand, let us consider the case where the AP additionally assigns the empty slot in TIM_1 to n_7 so that n_7 can be regarded as a member of TIM_1 as well. For the same buffered traffic, the AP would set the block bit for TIM_1 only, since all the pending data at the AP can be delivered by just waking up TIM_1. In this setting, the number of unnecessary wake-ups is only 2, n_2 and n_3, and the remaining STAs (i.e., all STAs in TIM_2 except n_7) can stay in low-power state. It is worth mentioning that as it can be seen in Section. VII, the gain of the proposed method increases with the network size; in other words, the unnecessary wake-up problem deteriorates as the number of STAs on the network increases. This temporary membership change approach does not require a STA to re-associate or any change in the management/organization of the entire STAs. In addition, as discussed in Section. VI, it does not increase the expected delay to data delivery.

III. RELATED WORK

There have been many articles welcoming/appreciating the new era of 802.11ah by introducing its noteworthy features as well as its potential to realizing many IoT applications [7] [10] [18] [19] [20]. However, only a little amount of research effort has been made to enhancing the energy efficiency of a large-scale 802.11ah network.

Wang et al. [21] [22] studied how the number of devices and the duration of RAW affect the energy efficiency of UL communication. They also proposed an access window algorithm that finds an optimal number of competing devices and the RAW size. Park et al. [23] carried out a research similar to [21] in that they studied the relationship between the size of RAW and the number of STAs. In their proposed MAC enhancement, an AP determines the optimal size of RAW from the estimated number of STAs participating in UL transmission. The two studies focus on UL communications for 802.11ah with adjusting the RAW size.

Liu et al. [26] proposed an energy-efficient Offset Listen-Interval (OLi) algorithm for standard WLAN PS mechanism that evenly distributes the traffic (or STA) across different beacon periods to reduce the level of contention as well as the delay. When a STA sends a Power Saving request to an AP, the AP allocates the STA to a beacon period that has the minimum number of contending STAs. Their contention balancing scheme over beacon periods eventually decreases the power waste for channel access. In [24], the author studied the signal estimation problem in a cooperative 802.11ah network with relays in order to minimize the power consumption. The proposed method in [24] calculates the optimal power for each STA considering the location of the fusion center and the relay.

Ogawa et al. [25] proposed an enhanced power saving method for 802.11ah with virtual grouping to reduce the power consumption when the network is congested. Using the random AIFSN scheme, STAs are classified into either contending or non-contending status, by which the number of contending STAs is limited. Also, during operation, a STA switches to sleep state based on the number of idle states it experiences. Ji et al. [27] questioned the efficiency of the 802.11ah TIM structure. They proposed a TIM compression scheme in order to support communications in a dense network as well as to enhance the throughput efficiency. Qutab-ud-din et al. [28] considered operating an 802.11ah network under the communication regulations on sub-1 Ghz band. To this end, they showed how the throughput performance is affected by the duty cycle, which is what network devices operating on sub-1 GHz must abide by. In spite of such contributions they made, the last two studies left the energy efficiency of 802.11ah unexplored.

In order to increase channel utilization, Chang et al. [16] proposed a grouping strategy for a saturated 802.11ah network with heterogeneous traffic demands. Their proposed scheme distributes STAs over groups such that the overall UL traffic rates are balanced. Zhao et al. [17] studied energy efficiency on 802.11ah networks for UL transmission. Their proposed scheme, FESM, allows STAs to switch to sleep state for a random amount of period when the channel is sensed busy. As a result, the level of contention as well as the amount of energy consumption for channel access can be reduced.

Lastly, performance analysis for 802.11ah networks has been carried out, mainly focusing on the restricted access scheme. Raeesi et al. [12] carried out a performance evaluation for 802.11ah networks by using the analytical model they proposed. They evaluated the performance and energy consumption for a 802.11ah network, and showed that the restricted access scheme affects the energy efficiency. Zhen et al. [15] studied the performance of 802.11ah networks with respect to the grouping-based restricted access strategy. They also analysed how the throughput performance varies as the length of the channel access period for each group changes. Similarly, Khorov [13] and Tian [14] evaluated the efficiency of restricted access mechanism of 802.11ah networks from the perspective of mathematical framework and simulation study, respectively. Badihi et al. [29] carried out a performance evaluation of 802.11ah network focusing on DL transmission. In particular, they studied the effect of network parameters, such as bandwidth and DTIM period, on latency and power consumption.

The proposed method in this paper is different from the aforementioned papers as follows. First, we consider an energy waste of the 802.11ah power saving mechanism on a single hop network, i.e., direct communication between an AP and its associated STAs, which is the basic model of 802.11ah. Secondly, the proposed method is compliant with 802.11ah, and works well with general configurations of STAs as opposed to some of the aforementioned works that are not. Also, the proposed scheme is suitable for online processing, and it does not require any significant changes to 802.11ah, such as resizing RAW or making changes to the hierarchical TIM/AID structure. Finally, this paper first addresses the unnecessary wake-up problem and the propose a unique, novel method that allows temporary membership changes, by which the number of STAs that can stay in sleep is maximized.

IV. NETWORK MODEL AND ASSUMPTIONS

We consider a single-hop 802.11ah sensor network where all STAs communicate directly with an AP on a shared wireless channel. We assume that traffic arrivals to STAs (e.g., actuation or control messages in DL) follow the Poisson distribution. The rate of each arrival is assumed to be known or can be learned by either an explicit notification or monitoring the traffic, respectively. Given the traffic rates, we classify the STAs into two groups; one is called *sensory* whose traffic arrival rates are small, and the other is called *controllable* whose incoming traffic rates are relatively large. Sensory STAs are the ones whose main task is sensing the environment or metering the usage of resources, and then they send the information in the UL. Therefore, their incoming traffic rates are low. On the other hand, the controllable STAs are the ones that frequently receive either control or actuation messages in the DL so that they can perform some designated actions/tasks or missions. We assume that the majority of STAs are sensory. However, we do not assume anything about the number of devices on the network and how the association/grouping has been made.

In the 802.11ah network, any STAs that want to join the network should make an association with an AP. As a result, STAs are given AIDs which also indicate to which TIM group each STA belongs. Let us denote this association as *primary association*, and the corresponding AID as *primary AID* (or P-AID). After the primary association is made, the proposed method runs the following two programs: *Secondary AID Assignment* and *Traffic Scheduling*. The Secondary AID Assignment program utilizes the unused AIDs, and makes additional associations between *some* STAs and groups so that those STAs can also associate with other groups in addition to the group they initially belong to by primary association. In other words, the Secondary AID Assignment program establishes a secondary membership, called *secondary association*, so that some STAs have two AIDs and thus, they can switch between the groups. The second AID to be given to some STAs as a result of the secondary association is called *secondary AID* (or S-AID for short). Once the secondary AID assignment is

Table II
SUMMARY OF NOTATIONS

M	Number of TIM groups
$\mathcal{G}$	Set of TIM groups, $\{g^{(1)}, g^{(2)}, ..., g^{(M)}\}$
$n_s^{(i)}$	Number of sensory STAs in $g^{(i)}$
$\mathcal{S}^{(i)}$	Set of sensory STAs in $g^{(i)}$, $\{s_1^{(i)}, s_2^{(i)}, ..., s_{n_s^{(i)}}^{(i)}\}$
$n_c^{(i)}$	Number of controllable STAs in $g^{(i)}$
$\mathcal{C}^{(i)}$	Set of controllable STAs in $g^{(i)}$, $\{c_1^{(i)}, c_2^{(i)}, ..., c_{n_c^{(i)}}^{(i)}\}$
$y^{(i)}$	Number of unused AIDs in $g^{(i)}$
$\Lambda^{(i)}$	Arrival rates of sensory STAs in $g^{(i)}$, $\{\lambda_1^{(i)}, \lambda_2^{(i)}, ..., \lambda_{n_s^{(i)}}^{(i)}\}$
$\mathcal{M}^{(i)}$	Arrival rates of controllable STAs in $g^{(i)}$, $\{\mu_1^{(i)}, \mu_2^{(i)}, ..., \mu_{n_c^{(i)}}^{(i)}\}$
η	Amount of energy waste from an unnecessary wake-up

made, the following traffic scheduling program checks if there is a chance to reduce the number of STAs that have to wake up unnecessarily. As illustrated by example in Section. II, if the pending traffic at the AP can be completely delivered by waking up less number of TIM STAs, then the AP re-arranges the traffic indication bits in both DTIM and TIM message by taking advantage of the S-AID.

V. PROBLEM FORMULATION: SECONDARY AID ASSIGNMENT

The first part of the proposed scheme is to establish secondary associations for *some* STAs if there are unused AIDs. Since the number of unused AIDs is limited, we cannot allow all STAs to establish the secondary association. In this regard, we propose to chose controllable devices and let them be assigned S-AIDs, since they are the ones that mainly cause frequent unnecessary wake-ups to other STAs. The classification of STAs into either sensory or controllable group depends only on their traffic arrival rates, which are, as aforementioned, known in advance or can be learned during operation. Before we proceed, please note that the notations used in the remainder of the paper are summarized in Table II.

A. Classifying Stations

The purpose of the classification is to make a list of controllable STAs which have higher traffic arrival rates, and eventually to pass the list to the Secondary AID Assignment program which decides whether or not to assign an S-AID to each STA in the list. Although the classification procedure can be as complex as we want it to be, we have chosen a simple algorithm in order for it to be scalable. One extremely simple, yet working, solution is to mark all STAs as controllable. However, it maximizes the search space for the secondary AID assignment problem and thus, it rather increases the overall runtime. In this regard, we have designed a simple algorithm, Algo. 1, which finds a threshold point by which STAs are classified.

Algorithm 1 Classification Algorithm

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1: for each $g^{(i)}$, i=1 to M do
2:     $R = \{r_1, r_2, \cdots, r_j, \cdots, r_{N^{(i)}}\}$        // traffic rates
3:     $R_{min} = \mathtt{min}(R)$, $R_{max} = \mathtt{max}(R)$
4:     $S \leftarrow$ number of steps
5:     $\Delta = (R_{max} - R_{min})/S$
6:     $sum^*,\ thr^* \leftarrow \infty$
7:     for t=1 to S-1 do
8:         $thr = R_{min} + t \cdot \Delta$
9:         $sum = \sum_{j=1}^{N^{(i)}} |thr - r_j|$
10:        if $sum < sum^*$ then
11:            $sum^* \leftarrow sum$, $thr^* \leftarrow thr$
12:        end if
13:    end for
14:    for each STA j=1 to N$^{(i)}$ do
15:        if $r_j \leq thr^*$ then
16:            $\mathcal{S}^{(i)} = \mathcal{S}^{(i)} \cup \{\text{STA-}j\}$        // mark as sensory
17:            $\Lambda^{(i)} = \Lambda^{(i)} \cup \{r_j\}$
18:        else
19:            $\mathcal{C}^{(i)} = \mathcal{C}^{(i)} \cup \{\text{STA-}j\}$        // mark as controllable
20:            $\mathcal{M}^{(i)} = \mathcal{M}^{(i)} \cup \{r_j\}$
21:        end if
22:    end for
23:    $n_s^{(i)} = |\mathcal{S}^{(i)}|$, $n_c^{(i)} = |\mathcal{C}^{(i)}|$
24: end for
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Algo. 1 iterates over each group and classifies STAs into one of the two groups, i.e., sensory or controllable. The set R (line 2) represents the traffic rates of all STAs in $g^{(i)}$, where $N^{(i)}$ is the number of STAs in $g^{(i)}$. The design parameter S (line 4) determines the number of iterations to search for the best threshold. The step size is equal to the range of traffic rates divided by S (line 5). On each iteration of the first inner for-loop (lines 7–13), the algorithm sets a threshold (line 8), calculates the sum of the distances between the threshold and all the traffic rates (line 9), and records the so-far the best threshold that minimizes the distance sum (lines 10–12). Then, in the later for-loop (lines 14–22), STAs are classified into either sensory or controllable by using the best threshold point.

B. Expected Power Consumption

As a reminder, the overall goal of the proposed method is to reduce the number of unnecessary wake-ups and thus, to reduce the overall energy consumption. In order to find a secondary association strategy that helps to reduce such wake-ups most, we first define the expected power consumption from the unnecessary wake-ups of sensory STAs[2]. Let us first define the following events: $A^{(i)}$:= there is at least one frame buffered at the AP for $g^{(i)}$ in time t (i.e., a DTIM interval); $a_j^{(i)}$:= there is at least one frame buffered at the AP for $s_j^{(i)}$ in time t; and $\neg a_j^{(i)}$:= there is no frame buffered at the AP for $s_j^{(i)}$ in time t. Also, let $p_j^{(i)}$ be the probability that, after time t, $s_j^{(i)}$ wakes up unnecessarily, meaning that $s_j^{(i)}$ has to wake up to receive a TIM beacon while there is no frame buffered for

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[2] Since the majority of the devices are sensory devices by the assumption, it does not make any notable difference whether or not we take the controllable devices into consideration for the following calculation.

it. Using the superposition property of the Poisson process and the independence of the arrival process, we can derive the following equations.

$$\begin{aligned} p_j^{(i)} &= Pr(A^{(i)})Pr(\neg a_j^{(i)}|A^{(i)}) && (1)\\ &= Pr(\neg a_j^{(i)} \cap A^{(i)}) && (2)\\ &= Pr(\neg a_j^{(i)})Pr(A^{(i)}_{-s_j^{(i)}}), && (3) \end{aligned}$$

where $A^{(i)}_{-s_j^{(i)}}$ is an event that $g^{(i)}$ is paged when $s_j^{(i)}$ is excluded from the group. Given that the number of sensory STAs in a TIM group is large and the their individual traffic rates are small, the right hand side of Eq. (3) approaches to $Pr(A^{(i)})$. This implies that with high probability a sensory STA will see no buffered frame for it whenever it has to wake up and listen to the TIM beacon. That is, in the event of $A^{(i)}$, a sensory STA is highly likely to waste energy because of its unnecessary wake-up. Based on this observation, we get the expected amount of energy waste in time t for sensory STAs in $g^{(i)}$ as: $Pr(A^{(i)}) \cdot n_s^{(i)} \cdot \eta$, where η is the amount of energy waste from an unnecessary wake-up, including the energy waste from making state transitions, receiving/processing a TIM beacon and staying in active state. Note that we only consider the energy waste from sensory STAs because the majority of STAs are sensory by assumption. In this regard, we conclude that the expected energy waste from a group is proportional to the total arrival rate to the group, and it is largely dependent upon the sum rate of controllable STAs whose arrival rates are relatively larger than that of sensory STAs.

Therefore, providing an additional membership to controllable STAs, not sensory, and allowing them to dynamically switch to another group will change the expected energy waste of the entire network to a large extent. In what follows, we propose the optimal secondary association program which selectively assigns the unused AID slots to some controllable STAs so as to minimize the number of unnecessary wake-ups.

C. Problem Formulation

The secondary AID assignment problem in P. 4 finds the best strategy $\mathbf{X}$ that allows some controllable STAs to make additional associations, and by which the number of sensory STAs that wake up for nothing is minimized. To this end, we have set a counter-intuitive objective function which is essentially to maximize the expected energy waste instead of minimizing it. Note that the proposed method provides an alternative or extra membership to some STAs (i.e., securing a freedom of switching between groups for some STAs), and leverages it in an opportunistic manner, while leaving the primary association as it is. The key idea of the proposed method is to opportunistically merge buffered traffic to a smaller number of groups so that the number of unnecessary wake-up events to sensory STAs is minimized. The opposite approach, e.g., balancing the sum traffic rate over TIM groups, does not help to reduce the number of unnecessary wake-ups.

The optimization problem P. 4 searches for the best secondary association strategy by which the overall expected energy waste is maximized. As a result, each group has a higher chance of turning other paged TIM groups into sleep by redirecting their traffic to itself, and serving them during its own TIM interval.

$$\max_{\mathbf{X}} . \sum_{i=1}^{M} \delta^{(i)} \qquad (4a)$$

subject to:

$$X_{j,(k)}^{(i)} \in \{0,1\}, \ \forall i,j,k \qquad (4b)$$

$$\sum_{\substack{i=1,\\ i\neq k}}^{M} \sum_{j=1}^{n_c^{(i)}} X_{j,(k)}^{(i)} \leq y^{(k)}, \ \forall k \qquad (4c)$$

$$\sum_{k=1}^{M} X_{j,(k)}^{(i)} = 1, \ \forall i,j \qquad (4d)$$

In the objective function Eq. (4a), the term $\delta^{(i)}$ indicates the increase in the expected amount of energy waste due to the associated controllable STAs in TIM group i, which is explained in detail as follows. As an extension of the previously defined event $A^{(i)}$, let us define the following two more events, $A_{+c}^{(i)}$ and $A_{-c}^{(i)}$. The event $A_{-c}^{(i)}$ represents the case that there is at least one frame pending at AP for TIM group $g^{(i)}$ when there is no controllable STA in the group. Similarly, $A_{+c}^{(i)}$ represents the same event except that it is for the case when the group has some controllable STAs, and which controllable STA to associate with is determined by the decision variable $\mathbf{X} = \{X_{j,(k)}^{(i)}\}$. In a mathematical expression, $\delta^{(i)}$ is defined as:

$$\begin{aligned} \delta^{(i)} &= [Pr(A_{+c}^{(i)}) - Pr(A_{-c}^{(i)})] \cdot n_s^{(i)} \cdot \eta \\ &= e^{-\sum_{j=1}^{n_s^{(i)}} \lambda_j^{(i)} t}(1 - e^{-\sum_{k=1}^{M} \sum_{j=1}^{n_c^{(k)}} \mu_j^{(k)} X_{j,(i)}^{(k)} t}) \cdot n_s^{(i)} \cdot \eta. \end{aligned}$$

The decision variable $X_{j,(k)}^{(i)}$ is binary by the constraint Eq. (4b), and it is 1 when a controllable STA j which already made a primary association with TIM group i is allowed to make a secondary association with TIM group k, and 0 otherwise. In this regard, $\delta^{(i)}$ measures how much more energy will be wasted if a TIM group $g^{(i)}$ allows controllable STAs to associate with the group compared to the case when the group does not allow any.

The second constraint Eq. (4c) indicates that, for each TIM group $g^{(k)}$, the number of secondary associations allowed should not to exceed the number of unused AID slots in the group. The reason why the index k is excluded at the outer summation is that if a controllable STA that belongs to $g^{(k)}$ by the primary association happens to associate with the same group again through the secondary association, it is regarded as the STA is not allowed to make a secondary association and thus, the STA does not actually occupy/consume any AID slot. At last, each controllable device is allowed to make only one secondary association by the constraint Eq. (4d).

D. Relaxation on Binary Constraints

The optimization problem P. 4 is not convex, in general, because of the combinatorial nature of the secondary AID

Algorithm 2 Iterative one-by-one removal

```
repeat
    Solve the relaxed optimization problem P. 5
    for each group i do
        $(j^*, k^*) = \arg\min_{\forall j,k} X^{(i)}_{j,(k)}$ s.t. $X^{(i)}_{j,(k)} \neq 0$
        Set $X^{(i)}_{j^*,(k^*)} = 0$
    end for
until all $X^{(i)}_{j,(k)}$ are binary
```

assignment whose complexity increases exponentially with the number of controllable STAs and the number of groups [32]. The problem as it is might be solved in a reasonable amount of time if the number of the binary variables is small, but that is not the case for a large-scale 802.11ah network where an AP can associate with up to ~8,000 STAs. In order to transform P. 4 into a tractable, convex optimization problem, the binary constraint in Eq. (4b) is relaxed into Eq. (5b) by letting each binary variable take any value in [0,1].

$$\max_{\mathbf{X}} . \sum_{i=1}^{M} \delta^{(i)} \tag{5a}$$

subject to:

$$X^{(i)}_{j,(k)} \in [0,1], \ \forall i, j, k \tag{5b}$$

constraints in (4c), (4d)

Due to the relaxation of the binary variable, however, $\mathbf{X}$ no longer tells a clear membership relation since it is highly likely to be a real number between 0 and 1, not a binary number. Still, the relaxed decision variables can be used in practice, for example, by interpreting them as either of the following two cases. One is to let $X^{(i)}_{j,(k)}$ be the time sharing factor that indicates the proportion of time that STA j in $g^{(i)}$ can be temporarily associated with $g^{(k)}$. The other is to let $X^{(i)}_{j,(k)}$ be the probability that a corresponding association is allowed for each time. Although both interpretations are practically feasible, they incur additional operational complexity to AP and energy consumption to devices due to the frequent change of secondary association; in the worst case, all STAs may have nonzero values for all X's.

E. Recovering the Binary Solution

In order not to cause the aforementioned extra operational complexity and energy consumption, we have applied a technique that iteratively obtains binary values from the non-binary solutions from P. 5. Iterative one-by-one removal algorithm [30] [31] [33] [34] recovers binary solutions from the relaxed ones as described in Algo. 2.

The Algo. 2 first solves the relaxed optimization problem P. 5. Next, it finds the nonzero minimum $X^{(i)}_{j,(k)}$ for each group. After forcing up to M number of such variables to be zero, the algorithm returns to Step 2 in line 2 and repeats the whole procedure until all decision variables $X^{(i)}_{j,(k)}$ are binary. Note that on each iteration, instead of forcing multiple variables to be zero, forcing one over all i, j and k would yield a better solution in terms of the optimality gap. However, as the number of both controllable STAs and TIM groups increases, the one-variable-per-iteration approach significantly increases the runtime of the procedure. In order to expedite the one-by-one removal procedure, we have introduced the inner fop-loop which iterates over each group and thus, the algorithm sets up to M variables to be zero for each outer iteration; in Section. VII-A, we show that the expedited version still yields a small optimality gap.

F. Notification Procedure

As a result of the Secondary AID Assignment procedure, some controllable STAs are chosen to be given S-AIDs. The chosen STAs need to know which AID slots they can additionally associate with, which can be done by one of the three methods in general, i.e., broadcast, unicast and piggyback [3]. Among those three, piggyback spends the least amount of energy in this case since it minimizes the number of bits to be transmitted. Thus, in order to efficiently notify the selected STAs of the decision on the secondary association (i.e., S-AIDs), an AP piggybacks an S-AID in the first data to be delivered to the corresponding STA. It is worth mentioning that the secondary association is a long-term decision, meaning that the notification is required only a few times for each chosen STAs during their lifetime. Since the number of controllable STAs is small, and the Secondary AID Assignment procedure chooses only some of them depending on the number of available AID slots, the contribution of the notification procedure to the network-wide energy consumption is trivial.

G. Discussion

According to [5, Section 4.3.1], "an AID can indicate a groups of STAs." Considering that the main cause of the unnecessary wake-up problem is for using a small number indicators (i.e., small number of bits in DTIM) to represent the pending traffic status for many STAs, it cannot be a solution to the unnecessary wake-up problem. Rather, it may worsen the problem because the maximum number of STAs that can be associated with a TIM group increases. However, the single-AID-for-many-STAs can be beneficial to the proposed scheme in this paper. The proposed method uses unassigned AID slots to make secondary association. In the worst case, if the network is so populated that there is no vacant slots at all, then the proposed scheme cannot make any secondary association.

However, if an AP can group multiple STAs and then, assign a single AID for them, the number of AIDs in use can be reduced. In other words, an AP can increase the number of unused/unassigned AIDs, and thus to secure more freedom in making secondary association. In sum, if the single-AID-for-many-STAs is used, the proposed method can make more secondary association for the increased number of vacant AID slots. The tradeoff is an increased complexity. Since an AID no longer clearly indicates a physical STA, there should be a mechanism to identify which physical STA is referred to when an AID is paged. Since we are focusing on a low-complex, online scheduling scheme in this paper, we assume the basic mode, i.e., an AID refers to a single physical STA.

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[3] Piggyback can be regarded as a special type of unicast.

VI. ALGORITHM DESIGN: TRAFFIC SCHEDULING

In this section, we propose a traffic scheduling algorithm that minimizes the number of unnecessarily waking up sensory STAs by taking advantage of the secondary associations made by the Secondary AID Assignment procedure. On each DTIM interval, an 802.11ah-compliant AP constructs a traffic indication map for each group by using P-AID; let us denote this TIM message by *default* TIM. In the proposed scheme, the AP also checks if it can reduce the number of unnecessary wake-ups by using the secondary associations without missing any data to deliver. If it can, the AP rearranges traffic delivery; if not, the AP uses the default TIM as it is.

A. Exhaustive Search

Intuitively, the optimal traffic scheduling strategy can be found by exhaustive search. It schedules the buffered traffic in all possible ways and chooses the best one that minimizes the number of unnecessary wake-ups. To be specific, the exhaustive search algorithm first enumerates all possible permutations out of M TIM groups. Let us denote $\mathcal{P}$ as the set of permutations which has $M!$ elements, where the i^{th} element $p_{[i]} = \{g_{[1]}, g_{[2]}, \cdots, g_{[M]}\}$ is an ordered list of M TIM groups. Note that $g_{[1]}$ is the first element in the list $p_{[i]}$ and it does not necessarily need to be $g^{(1)}$. On the i^{th} iteration, the AP takes a list $p_{[i]}$ from $\mathcal{P}$. Starting from $g_{[1]}$, the AP rearranges the traffic delivery such that as many P-AIDs and S-AIDs in the TIM group can be utilized as possible if there is buffered traffic associated with those. Then it moves on to $g_{[2]}$ and so on up to $g_{[M]}$. After iterating over all elements in $\mathcal{P}$, it chooses the one with the least number of unnecessary wake-ups.

B. The Proposed Fast Traffic Scheduling

Although the exhaustive search guarantees to yield the optimal scheduling strategy, it is not suitable for an on-line processing for a large-scale network due to the high computational complexity. Also, it consumes a large memory space because it has to temporarily store all possible permutations of entire groups. In this regard, we propose a lightweight, fast traffic scheduling algorithm that yields a comparable performance to the exhaustive search without causing the aforementioned overhead. The proposed traffic scheduling algorithm is composed of three steps in sequence: 1) Feasibility Check, 2) Preprocessing, and 3) Traffic Scheduling.

1) Feasibility Check: The proposed algorithm first checks if it is possible to reduce the number of unnecessary wake-ups by examining the paged status of sensory STAs. Since sensory STAs are not able to change their membership, having a buffered data for a sensory STA implies that the group to which the STA belongs cannot help but waking up so as to listen to the TIM message. If every group has at least one paged sensory STA, there is no room for improvement. Therefore, the proposed algorithm immediately terminates, and the AP uses the default DTIM and TIM as they are for delivering the buffered frames. On the other hand, if there is at least one group that does not have any paged sensory STAs, there might be a chance that the group can stay in sleep even if some controllable STAs in the group are paged. In such a case, the proposed algorithm proceeds to the next Preprocessing procedure.

2) Preprocessing: The main purpose of having the preprocessing stage is to reduce the complexity of the following Traffic Scheduling procedure. As aforementioned, a TIM group with at least one paged sensory STA must wake up. Therefore, letting paged controllable STAs which made secondary association with such a must-wake-up group switch to the group does not increase (or may decrease) the number of overall unnecessary wake-ups. As a result, the must-wake-up TIM groups schedule as much traffic as possible by using both P-AID and S-AID, and then their scheduling is finalized. Now, the remaining groups are either of the following two cases: 1) that do not have any paged STAs, or 2) that only have one or more paged controllable STAs. For groups that belong to the former case, finalize their schedule as they are. Finally, the remaining groups are the ones that belong to the later case. If the number of the remaining groups is less than or equal to 1, terminate the procedure and return the updated traffic delivery schedule; otherwise, proceed to the Traffic Scheduling procedure.

3) Traffic Scheduling: This stage determines a traffic delivery schedule that minimizes the number of unnecessary wake-ups by leveraging the secondary association which allows some STAs to temporarily change their membership. Given that the remaining groups are the ones that have buffered traffic at AP only for controllable STAs, the traffic scheduling procedure runs as follows. First, it calculates the cost $c(i)$ for all remaining groups by using Eq. (6):

$$c(i) = \frac{1}{n^p(i)}(\alpha \cdot \check{n}_c^p(i) + \check{n}_c^s(i)), \tag{6}$$

where i is the group index, $n^p(i)$ is the number of STAs associated with group i through P-AID (i.e., $n^p(i)$ is the number of STAs to wake up if the group is paged), $\check{n}_c^p(i)$ is the number of paged controllable STAs associated with group i through P-AID, $\check{n}_c^s(i)$ is the number of paged controllable STAs associated with group i through S-AID, and α is a positive weight to $\check{n}_c^p(i)$. Next, the algorithm selects the group with the maximum cost. If there are multiple groups with the same, maximum cost, the one with the smallest index will be chosen. The algorithm, then, schedules as much traffic as possible to the chosen group by utilizing both P-AID and S-AID. These steps iterate until there is no more group to schedule. According to the Eq. (6), the group that has a smaller number of STAs to wake up (if paged), and also has a larger number of paged STAs will be chosen first for having a largeer cost value. In addition, the design parameter α is set to $1 + 1e - 10$ so as to further reduce the number of wake-ups by assigning a slightly larger weight to the controllable devices with P-AID than those with S-AID.

The overall procedure of the proposed scheduling algorithm is shown in Algo. 3, where $\mathcal{T}$ is the set of the default DTIM and all TIM messages. Please note that the traffic delivery for those groups that are not mentioned in the algorithm will be made as specified by the default TIM. Compared to the exhaustive search method of which search space (i.e., the

Algorithm 3 Proposed Traffic Scheduling Algorithm

```
Input: $\mathcal{G}, \mathcal{T}$        // TIM group, default DTIM/TIM info.
// 1) feasibility check:
if every group has paged sensory STA then
    Return $\mathcal{T}$ and terminate
end if
// 2) preprocessing:
for each group $g^{(i)} \in \mathcal{G}$ do
    if $g^{(i)}$ has paged sensory STA then
        Schedule as much traffic as possible to S-AID in $g^{(i)}$
        Update $\mathcal{T}$
        $\mathcal{G} \leftarrow \mathcal{G} - \{g^{(i)}\}$
    end if
end for
if $|\mathcal{G}| \leq 1$ then
    Return $\mathcal{T}$ and terminate
end if
// 3) traffic scheduling:
repeat
    Calculate the cost $c(i)$ for $\forall g^{(i)} \in \mathcal{G}$
    $i^* = \min \{\arg\max_i c(i)\}$
    Schedule as much traffic as possible to S-AID in $g^{(i^*)}$
    Update $\mathcal{T}$
    $\mathcal{G} \leftarrow \mathcal{G} - \{g^{(i^*)}\}$
until $\mathcal{G}$ is empty
Return $\mathcal{T}$ and terminate
```

number of groups to be explored) is $\Theta(M!)$, the proposed scheduling algorithm reduces it down to O(M).

It is worth mentioning that the expected amount of additional delay caused by the proposed method is zero compared to 802.11ah. On each DTIM interval, the proposed scheme delivers exactly the same amount of traffic that 802.11ah has scheduled to. In addition, the expected amount of delay within a DTIM interval is also zero. Let $d^{(i)}$ be such a delay that STAs in $g^{(i)}$ experience on traffic delivery, which is defined as:

$$d^{(i)} = \sum_{j=1}^{n_c^{(i)}} \sum_{k=1}^{M} Pr(X_{j,(k)}^{(i)} = 1)\tau_{i,k}, \tag{7}$$

where $\tau_{j,(k)}^{(i)}$ is an increase/decrease in time to traffic delivery when a STA j in $g^{(i)}$ by P-AID is served in $g^{(k)}$. We have $\tau_{j,(k)}^{(i)} > 0$ if $g^{(k)}$ is served after $g^{(i)}$, $\tau_{j,(k)}^{(i)} < 0$ if $g^{(k)}$ is served before $g^{(i)}$, and $\tau_{j,(k)}^{(i)} = 0$ if $k = i$. Note that sensory STAs are not allowed to change their membership and thus, they do not contribute to $d^{(i)}$ at all. Since we do not make any assumption on how the primary association is made, an event $X_{j,(k)}^{(i)} = 1$ is regarded to be equally likely among all possible $k = 1, 2, \cdots, M$. Then, the expected amount of delay increase cancels that of decrease and therefore, Eq. (7) becomes zero. That is, the expected delay caused by the proposed method is zero.

VII. EVALUATION

We have implemented both the optimal Secondary AID Assignment problem and the Traffic Scheduling algorithm on CVX [35] and MATLAB [36], and compared the performance of the proposed scheme to 802.11ah and the exhaustive search method. Evaluation has been performed with various number of TIM groups, each of which can associate with up to 64 STAs [8]. Also, we consider TIM groups in a single page, which can associate with up to 2048 STAs in total. Due to the advanced antenna technology, an AP can interact with STAs in one page independently from the rest, for example, by using the sectorized beam operations [5]. Therefore, the results to be shown in this section should remain the same whether or not we consider multiple pages at the same time. The traffic arrivals follow the Poisson distribution whose mean value is randomly chosen. Also, the primary association is randomly made and thus, each group is highly likely to have different number of STAs and different sum traffic rate from the rest. Each data point on the figures in this section is an average of several runs of simulation, except Fig. 9. To be specific, we have run 10 simulations for both Fig. 3 and Fig. 4. Also, for Fig. 5, Fig. 6, Fig. 7 and Fig. 8, we have run 100 simulations. For each data point in those figures, we have marked a 95% confidence interval. Please note that we have omitted the result of the case when $M = 1$, since the scenario is too simple and it does not allow any secondary associations to make; in other words, there will be no performance difference between the proposed scheme and 802.11ah.

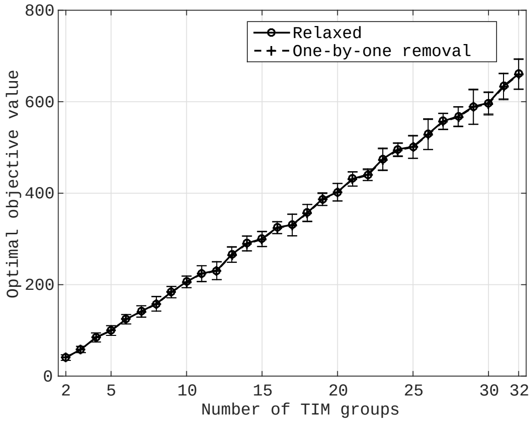

Figure 3. Comparison of the optimal objective values between the relaxed problem solution and the recovered binary solution.

A. Secondary AID Assignment & Optimality Gap

As discussed in Section V, we have applied relax-and-recover approach (Algo. 2) to the Secondary AID Assignment problem in order to maintain the overall complexity low and to make the initial problem (P. 4) tractable. Considering that the objective value of the original problem P. 4 is upper-bounded by the relaxed problem P. 5, and lower-bounded by the recovered binary solution, we first show that the optimality gap between the two bounds is tight, implying that the recovered binary solution has a high accuracy.

The Fig. 3 shows how the objective value changes as the number of TIM groups increases. In the figure, *Relaxed* and *One-by-one removal* correspond to the solution of the relaxed

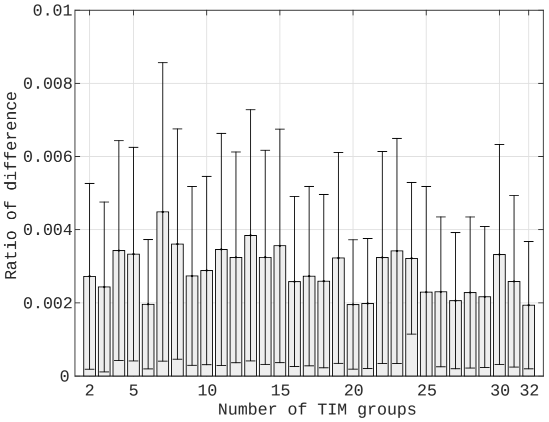

Figure 4. The ratio of the difference between the objective values of the relaxed and the recovered binary solution to the objective value of the relaxed solution.

association problem P. 5 and the recovered binary solution from running Algo. 2, respectively. Although the objective value of the relaxed problem is always larger than that of the recovered solution, the difference is small, meaning that the recovered solution has high accuracy. Also, we have measured the relative error between the two solutions as shown in Fig. 4. The y-axis denotes the ratio of difference between the two objective values to the objective value of the relaxed problem. Throughout all scenarios with different number of TIM groups, the mean error ratio never exceeds 0.005. That is, the bounds on the initial problem P. 4 are small and thus, the recovered solution is close to the optimum.

B. Traffic Scheduling & Number of Unnecessary Wake-ups

Next, we introduce the simulation results to show how effective the traffic scheduling algorithm is in terms of the number of unnecessary wake-ups. We compare the number of such energy-wasting wake-ups between 802.11ah, exhaustive search and the proposed method. Since the three methods deliver exactly the same amount of traffic on each DTIM interval, having a smaller number of wake-ups yields a better energy efficiency.

Both Fig.5 and Fig. 7 show the mean number of total unnecessary wake-ups with different number of TIM groups. Note that due to the high complexity of the exhaustive search method in terms of time and memory space, we were able to run it with up to 10 TIM groups of which results are shown in Fig.5. The proposed method, on the other hand, has a short response time and requires only a small memory space. Thus, we have carried out all possible scenarios, i.e., with up to 32 TIM groups, as shown in Fig. 7. As it can be seen in Fig.5, both exhaustive search and the proposed algorithm outperform 802.11ah in terms of the number of unnecessary wake-ups. As the number of both TIM groups and STAs increases, a larger freedom in making secondary association is exploited and thus, the performance enhancement compared to 802.11ah becomes larger for both exhaustive search and the proposed algorithm. It is noteworthy that the proposed scheme yields a comparable performance to the exhaustive search solution, although it has a much smaller computational and resource overhead. In addition, we have counted the number of unnecessary wake-ups for sensory STAs separates from that for controllable STAs as shown in Fig. 6. Since there are more

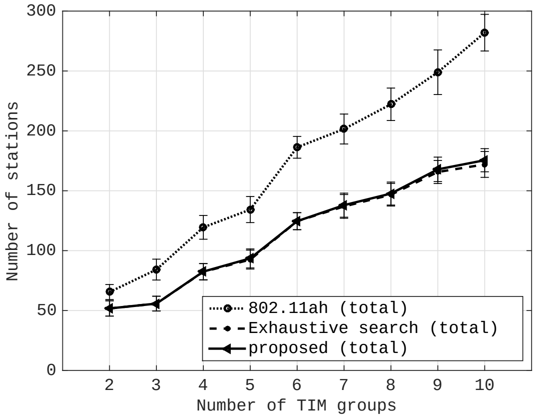

Figure 5. The mean number of unnecessarily waking-up STAs per DTIM interval with different number of TIM groups.

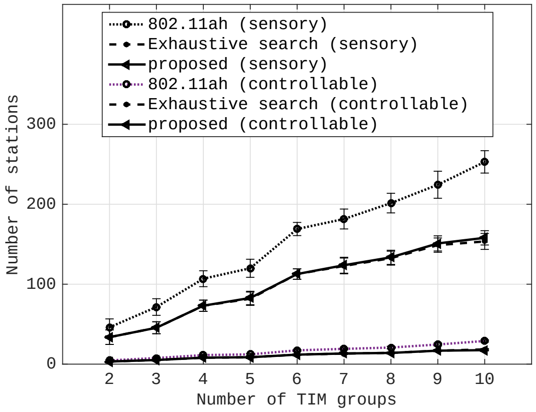

Figure 6. The mean number of unnecessarily waking-up sensory and controllable STAs per DTIM interval with different number of TIM groups.

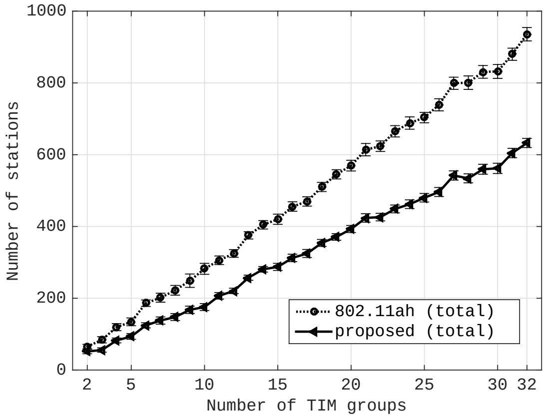

Figure 7. The mean number of unnecessarily waking-up STAs per DTIM interval with different number of TIM groups.

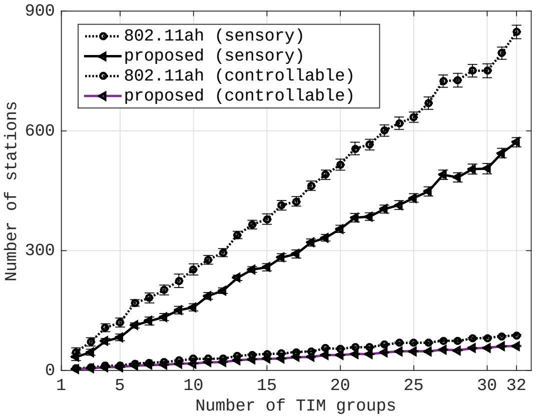

Figure 8. The mean number of unnecessarily waking-up sensory and controllable STAs per DTIM interval with different number of TIM groups.

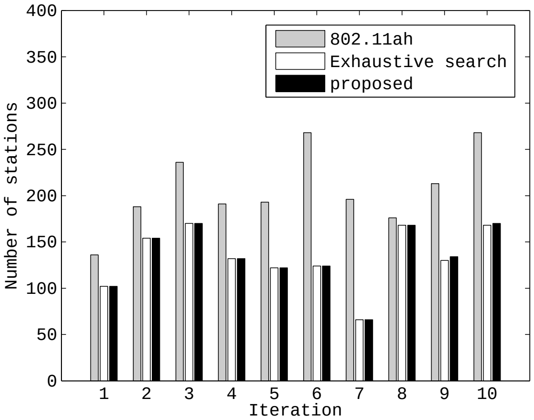

Figure 9. Example: the number of unnecessarily waking-up STAs during the first 10 iterations when the number of TIM groups is 8.

sensory STAs than controllable by assumption, three lines with larger values than the rest indicate the number of unnecessary wake-ups for sensory STAs, while the three with lower values are for controllable STAs. As it can be seen in the figure, 802.11ah produces the largest number of unnecessary wake-ups for both sensory and controllable STAs. Although the Secondary AID Assignment problem focuses on minimizing energy waste from sensory STAs, both the proposed method and the exhaustive search still outperform 802.11ah in terms of the energy waste from controllable STAs as well.

The following Fig. 7 shows the number of unnecessary wake-ups for both 802.11ah and the proposed method as the number of TIM groups increases up to 32. Again, we have separately shown the unnecessary wake-ups for sensory and controllable STAs in Fig. 8. As the number of both TIM groups and STAs increases, the difference in the number of unnecessary wake-ups becomes larger between 802.11ah and the proposed scheme, meaning that the proposed scheme brings more gains to enhancing energy efficiency. For instance, when there are 32 TIM groups, the proposed scheme, on average, incurs 632.6 unnecessary wake-ups, while 802.11ah does 935.7.

The performance enhancement in [0,1] scale can be measured by the ratio of the difference in the number of unnecessary wake-ups between 802.11ah and the proposed scheme to that of 802.11ah. Except the case of $M = 2$ which results in a ratio of 0.210, the performance enhancement is between 0.303 and 0.378 for the rest of M values, meaning that at least 30% of more devices are able to stay in low-power state when the proposed scheme comes into play compared to the 802.11ah power saving mechanism. As a reminder, both schemes deliver exactly the same amount of traffic, and the proposed scheme causes, on average, zero delay compared to 802.11ah.

As studied in [37], the basic power model for power consumption of the receiving circuitry can be modeled as a constant. Therefore, the amount of energy waste due to the unnecessarily waking-up STAs can be simply approximated by a linear function of the number of unnecessary wake-ups, in addition to the constant power usage for staying in active state. Considering the expected lifetime of 802.11ah STAs, and the number of DTIM intervals that STAs are expected to encounter during operation, reducing the number of unnecessary wake-ups will significantly prolong the lifetime of STAs as well as the whole network.

Yet, the computational and memory efficiency of the proposed scheme comes at the expense of the performance degradation compared to the exhaustive search method as shown in Fig. 9. On iterations 9 and 10, exhaustive search outperforms the proposed method in terms of the number of unnecessary wake-ups. However, the amount of performance degradation is trivial, and it becomes negligible as the iteration goes on as shown in Fig. 5.

VIII. CONCLUSIONS

In this paper, we have studied a large-scale IEEE 802.11ah wireless sensor network. In particular, we have focused on the energy efficiency of power saving mechanism on top of TIM and page segmentation. To reduce the power consumption of battery-operated sensor devices, we have proposed a novel way of utilizing unused AIDs and scheduling traffic delivery so as to reduce the number of unnecessary wake-ups. The proposed temporary membership change scheme allows the traffic scheduling algorithm to exploit a certain level of freedom in delivering buffered traffic and thus, the number of unnecessary wake-ups is minimized. In order to expedite the entire procedure, the relaxation and recovery scheme is applied to the optimization program, and a lightweight traffic scheduling algorithm is proposed. The evaluation results show that the proposed algorithm can significantly increase the number of sensor devices that can stay in low-power state, which could prolong their lifetime without increasing delay to traffic delivery.

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