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Energy-Efficient Sensor Grouping for IEEE 802.11ah Networks With Max-Min Fairness Guarantees

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ABSTRACT For the large scale wireless networks, restricted access window (RAW) mechanism is a promising technique for realizing large-scale sensor access with the limited collision probability. In this paper, we are committed to designing the traffic distribution based sensor grouping scheme to balance the energy efficiency (EE) of different groups in the large scale access networks. Specifically, by adopting the Markov chain model, we formulate the optimization problem of max–min EE by taking into account traffic demands with even distribution of different all groups, but the formulated problem is an integer nonlinear programming (INLP) problem. In order to solve the INLP problem, we propose an optimal traffic grouping algorithm (OTGA) by utilizing the branch-and-bound method (BBM) to accommodate for the congestion level among groups. Though the traffic demands of each group can be obtained from the traffic grouping scheme, different combination of heterogeneous sensors can generate the same traffic demands, which make it difficult to find the optimal solution of sensor grouping from the proposed traffic grouping scheme. Furthermore, a heuristic traffic-sensor mapping algorithm (HTMA) is presented to make the traffic demands of each group appropriate. Thus, the proposed scheme can achieve a sub-optimal performance with the individual EE. The numerical results are provided to verify the effectiveness of the proposed schemes.

INDEX TERMS IEEE 802.11ah, energy efficiency, sensor grouping, combination optimization.

I. INTRODUCTION

A. MOTIVATION

Over the last decade, the explosive growth of consumer-oriented multi-media applications, a large number of end devices, such as smart phones, wearable devices and vehicles, need to be connected by means of mobile communication network [1]. This has triggered the rapid use of the unlicensed band to offload the traffic of Internet of Things (IoT) communications, where millimeter wave technology has been regarded as a promising candidate for IoT networks [2], [3]. However, the legacy IEEE 802.11 protocols operating on 2.4 GHz or 5 GHz band were designed for small-scale networks, which are difficult to meet the access requirements in large-scale wireless network. Thus, IEEE 802.11ah has been put forward for supporting large-scale sensors access, which operates in sub 1 GHz spectrum. The protocol allows an access point (AP) to support up to more than 8000 nodes with the transmission range up to 1 km at the rate of more than 100kbps [4]–[6]. The target of the standard is to ensure widespread connectivity, high throughput, low energy consumption and high scalability.

Since the 802.11ah standard still uses CSMA-based channel access protocol, the increasing number of sensors would result in intensified collisions. In order to solve this problem, a Restricted Access Window (RAW) mechanism has been proposed in the latest draft of the IEEE 802.11ah standard [7]. In particular, the RAW mechanism divides sensors into groups, partitions the channel time into multiple RAW slots. AP assigns each group to one RAW slot and broadcast the allocation information in beacon frame. In the assigned RAW slot, the nodes are allowed to contend for

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uplink channel access but go dormant in other RAW slots. RAW mechanism limits the uplink channel access to a small number of sensors at a time slot and spreads their uplink access attempts over a long period of time. Thus, the RAW mechanism can effectively and efficiently reduce the energy consumption and overhead of contention.

Generally, the power of sensors in the IoT networks is limited, because of the constraints on physical structure of the sensors [8]–[11]. Therefore, the energy efficiency (EE) problem over the IoT networks is also an attractive topic, especially for the case that a large number of sensors associate with one AP at the same time. In the case of limited channel time, if each sensor chooses a RAW slot by taking not account to the traffic distribution among all groups, the sensors will randomly access the RAW slot so that those user groups with heavy taffic will waste more time and energy for contention, while the groups with light traffic will remain idle channel time that no packet could be transmitted.

Conventional random grouping strategy in IEEE 802.11 ah standard can improve uplink EE by optimizing the combination of the size of RAW and the number of nodes in each RAW [12], [13]. However, using this strategy, the part of RAWs will suffer from heavy traffic and spend more time and energy for contention, which may make the system outage. This motivates us to design the effective sensor grouping strategy to guarantee the EE fairness among groups for heterogeneous 802.11ah networks.

B. RELATED WORKS

IEEE 802.11ah relies upon the RAW based Medium Access Control (MAC) protocol and the transmission quality of data depends on the contention level among co-channel competitors. Therefore, reducing the contention for spectrum access among a large number of devices becomes a key problem for the dense machine type clients.

To address the channel contention problem, various MAC algorithms have been proposed [14]–[16]. In general, since the AP affects the optimal size of RAW, a MAC enhancement algorithm was proposed to improve the successful probability for uplink access channel by using the Maximum Likelihood estimation methods to estimate the number of stations contending [14]. Furthermore, an access control strategy performed at the AP was proposed [15], which can effective improve the access efficiency by limiting the number of contending nodes. Additionally, conventional studies thought that the duration of each RAW slot should be the same in the entire RAW frame [12]–[14]. While, based on the positive correlation between the duration of each RAW and the size of the group [16], the authors proposed a novel model, where a RAW frame is divided into two sub-frames and the duration of RAW slots in each sub-frame is chosen according to the size of the group. As a result, throughput enhancement of restricted access window for uniform grouping scheme have been obtained.

Moreover, a potential technique to alleviate the channel contention is to use the grouping strategy [17]–[23]. Sensor grouping strategy is early applied in the network throughout and delay [17], [18]. For the normalized throughout and delay, sensor grouping is an effective approach to alleviate channel contention by conducting the comprehensive throughput and delay with the consideration of unsaturated traffic conditions and hidden node events [17]. Compared with [17] and [18] that the grouping processing usually be implemented by the centralized approach, group-synchronized distributed coordination function were proposed for densely deployed wireless networks with a large number of stations, and the decentralized grouping scheme can achieve a throughput similar to that of the centralized grouping scheme, especially for the dense networks [19]–[20]. Furthermore, in the machine-to-machine (M2M) communication network, an analytical model to characterize the power save performance of M2M communication networks with a large number of nodes and periodic traffic was developed and an offset listening protocol by controlling station wake up times with calculated offsets was designed to dynamic schedule the stations during the different beacon periods [21], [22]. However, in the above grouping schemes, the heterogeneous traffic loads have not been considered in the proposed grouping schemes. To make full use of the channel, the efficient grouping algorithm need to consider the different transmission mode, a grouping strategy by joint considering traffic load, number of stations and RAW group duration was proposed to to derive the optimal number of RAW groups [23].

Furthermore, for the complex network that the nodes have the different traffic patterns, the allocation of the traffic demands in each group becomes the challenging problem [24]–[28]. Specifically, [24] proved that effective sensor grouping require to consider traffic demands of sensors. A real-time traffic-adaptive RAW optimization algorithm that improved uplink throughput was developed in [25], where AP adjusted RAW duration and assigned stations to RAW slots according to the estimated packet transmission frequency. In [26], a novel grouping algorithm for devices was proposed, where AP divided the nodes into several groups and assigned each group a priority according to the estimated transmission time. The group of devices with higher priority will spend more time to access the channels during the RAW duration compared to the lower priority devices. Furthermore, [27] proposed a load-balanced grouping algorithm to partition sensors into groups based on traffic distribution, which can improve channel utilization. A later work in [28] derived a regression-based analytical model to estimate contention success probability, which aimed at maximizing the minimum channel utilization among groups. Nevertheless, the EE was not taken into account in the these researches. Since sensors are mostly battery-powered, the EE of sensors is an important problem and needs to be considered.

Furthermore, there were some researches making efforts to improve the performance of EE in the uplink communication systems under the 802.11ah protocol [12], [13].

Wang *et al.* [12] considered the relationship between the EE performance and the number of node and duration of RAW, where an adaptive access window algorithm was proposed to find the optimal combination of the number of contending nodes and group size. Due to the random selectivity, part of slots will idle resulting the resource waste. To address the problem, a novel retransmission scheme was proposed in their later work [13], in this scheme, each node selects any RAW slot with equal probability, if it collides in its assigned RAW slot, it can retransmit its packets once again in next RAW slot. Thus, it can improve the probability of successful transmission and system EE. However, the scheme is limited by a dense network. When the number of nodes increases, the number of time slots required will also increase, so the retransmission mechanism will only intensify co-channel competition. Therefore, sensor grouping strategy is an effective strategy to reduce the channel contention.

C. OUR CONTRIBUTION

For simplicity of analysis, we assume that each RAW slot has equal number of contending IoT nodes [29]. As in [12] and [28], we also adopt the typical Markov Chain model to analyze the throughput and energy consumption and prove that the minimum EE of a group is maximized when traffic demands generated by each group are the same. Different from [12] and [28], we formulate sensor grouping based EE max-min as an integer nonlinear programming (INLP) model. Aiming at the INLP problem, we first relaxed it as a continuous problem, the solution of that can be obtained by reduction to absurdity. We then use the Branch-and-Bound method (BBM) to solve the integer problem and obtain optimal traffic grouping scheme. For a traffic grouping scheme, the traffic demands of each group can be obtained, but different combination of sensors can collect the same traffic demands, the sensor grouping scheme cannot be obtained from the proposed traffic grouping scheme. Thus, a heuristic traffic-sensor mapping algorithm (HTMA) is proposed to get sub-optimal solution.

The main contributions of this paper are summarized as follows.

- *New Problem Formulation*: We formulate sensor grouping based max-min EE among groups as an integer nonlinear programming (INLP) problem in heterogeneous scenarios. A Markov Chain model is adopted to compute the throughput and energy consumption for different groups and derive the optimal solution of the max-min EE by using the method of reduction to absurdity when the overall traffic demands are evenly divided among all groups.
- *Optimal traffic grouping algorithm*: Aiming at the non-convex INLP problem, we propose an optimal traffic grouping algorithm (OTGA) based on the Branch-and-Bound method (BBM) to find the optimal solution of traffic grouping scheme of the formulated problem. For the proposed traffic grouping algorithm, we can obtain the traffic demands of each group. Different combinations of sensors can generate the same traffic demands, thus, it is difficult to get the sensor grouping scheme from the proposed scheme.
- *Sub-optimal sensor grouping algorithm*: We propose a heuristic traffic-sensor mapping algorithm HTMA) to obtain a sub-optimal solution. Specially, sensors with heavy traffic are grouped evenly first and then sensors with light traffic are divided into groups with low traffic to ensure traffic balanced among groups.

The remainder of the paper is organized as follows. Section II introduces our system model and formulates the max-min EE problem. The proposed traffic grouping scheme is presented in Section III. In Section IV, we propose a heuristic traffic-sensor mapping algorithm to obtain a sub-optimal solution of the sensor grouping scheme. Performance evaluations are presented in Section V, and finally Section VI concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first provide a simplify introduction to 802.11ah MAC, then present the system model and sensor grouping strategy. After that, we formulate sensor grouping problem to maximize the minimal EE among groups.

A. REVIEW OF GROUPING-BASED MAC PROTOCOL of IEEE 802.11ah

By leveraging the RAW operation, IEEE 802.ah standard can apply a grouping-based MAC protocol. Specifically, the sensors in wireless network are divided into several groups by exploiting RAW mechanism. The channel time is also partitioned into beacon intervals. Each of which is divided into a number of equal-duration RAW slots, and each RAW slot is assigned to a group of sensors as shown in Fig.1. Since the RAW mechanism limits the number of sensors contending for access channel, collision probability can be significantly decreased. When sensors associate with an AP, they can report the information required by grouping and the AP can update the information of sensors periodical. All sensors listen to the header of beacon frame to obtain allocation information that indicates which RAW they are belonged to, then they would turn to sleep mode until their RAW slot come to access channel through CSMA-based contention mechanism, i.e., distributed coordination function (DCF). At the end of their allocated RAW, sensors would go to sleep and wake up at the start of the next beacon transmission time to save energy.

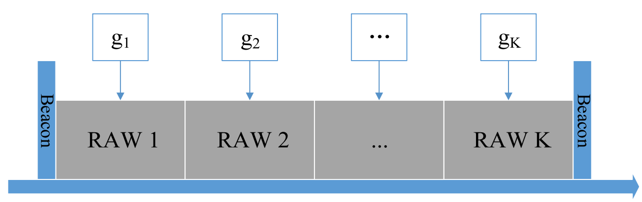

FIGURE 1. RAW assignment procedure in the grouping scheme.

The binary exponential backoff scheme is implemented by DCF. Generally, a station require the channel state information before sending the packets to the AP. If the channel keeps idle for distributed interframe space (DIFs), the nodes uniformly choose a backoff counter within the limited contention window size. At the beginning of the backoff interval, if the collision occur, the contention window size continue to double till the threshold. Otherwise, the backoff counter is decremented until to the zero. Up to now, the sensors start to transmit their packets to AP. On the other hand, if the channel is operating at the full capacity, the backoff counter is in suspend mode though to releasing the new unoccupied channels.

B. SYSTEM MODEL

In this paper, we consider the uplink transmission of IEEE 802.11ah IoT network with N sensors and one AP, where the sensors collect data periodically and then transmit the collected date to the AP via packets. For each beacon interval, sensors and channel time are partitioned into K groups and K RAWs, each sensor group can be indexed as $g_1, g_2, \ldots, g_K$, with $\mathcal{K} = \{1, 2, \cdots, K\}$ denoting as the set of RAWs. Based on the sensor grouping and the RAW model in [16], all sensors in any group is assigned to a random RAW $j, j \in \mathcal{K}$.

For the IoT network environment, lots of sensor contentedly access the RAW slots. We assume that each RAW slots have the same number of sensors so as to make the readers easily comprehend the proposed grouping-based scheme. In the dense IoI networks, the network contains M types of sensors and the set of sensors in each type m be denoted as $\mathcal{T}_m$ for $m = 1, 2, \ldots, M$. Each sensor of type i has a sampling rate λ_i and the packet length L_i, which determine the traffic demands it collects. Let d_m and D_j be the traffic demands generated by a sensor of type m and the total traffic demand generated by sensors of group j in a beacon interval. Define T_i as the number of sensors of type i, i.e., $|\mathcal{T}_i| = T_i$. Denote the number of sensors of type i in group j by T_{ij}, and the set of sensors by $\mathcal{T}_{ij}$, respectively, i.e., $\left|\mathcal{T}_{ij}\right| = T_{ij}$. Since different combinations of sensors can get the same traffic demands, we cannot get a sensor grouping scheme from a determined traffic grouping scheme.

Let $\mathcal{G}$ be the set of all possible sensor grouping, and all sensors are divided among all groups. Define a sensor grouping scheme $\boldsymbol{g} \in \mathcal{G} = [\mathcal{G}_1, \mathcal{G}_2, \mathcal{G}_3, \cdots, \mathcal{G}_K]$ as the vector indicating the sensors allocated to all groups, where $\mathcal{G}_j$ denotes the set of sensors allocated to group g_j. Each sensor must join one group, and can only join one group. Different sensor grouping schemes will change the distribution of traffic demands in the system. We then let $\boldsymbol{\mathcal{D}} = [D_1, D_2, \cdots, D_K]$ be the traffic grouping scheme under $\boldsymbol{g}$ which indicates traffic distribution among all groups, where D_j is the traffic demands generated by sensors allocated to group g_j in a beacon interval.

To further understand the concept of sensor grouping strategy, a toy is given in Appendix.

C. PROBLEM FORMULATION

It is well known that sensor grouping strategy can effectively reduce the collision probability. However, for the large number of sensors in the IoT network, the energy efficiency also needs to be considered.

Let $R_j(\boldsymbol{g})$ and $E_j(\boldsymbol{g})$ denote the data rate and energy consumption of group g_j under $\boldsymbol{g}$, respectively. Based on $R_j(\boldsymbol{g})$ and $E_j(\boldsymbol{g})$, we formulate the problem to maximize the minimum EE among groups via traffic-aware sensor scheduling design under a large number of senors environment, which can be expressed as

$$\begin{aligned} \mathcal{P}1: \max_{\boldsymbol{g}} \min \quad & \eta_j^{EE}(\boldsymbol{g}) = \tfrac{R_j(\boldsymbol{g})}{E_j(\boldsymbol{g})} \\ \text{s.t.} \quad & \text{C1}: D = \sum_{j=1}^{K} D_j(\boldsymbol{g}). \end{aligned} \tag{1}$$

In order to address problem $\mathcal{P}1$, the close-form solution of date rate $R_j(\boldsymbol{g})$ and energy consumption $E_j(\boldsymbol{g})$ need to be derived. Motivated by Markov chain model [29]–[36], which can be used to analyze throughput in the IEEE 802.11ah. Aiming at the traffic-balanced sensor grouping strategy, in this paper, we also adopt the Markove chain model to formulate the expression of system thoughput and energy consumption to balance traffic in the sensor grouping strategy. Specifically:

1)throughput and energy consumption computation: Considering the channel access protocol of DCF. The sensors in each RAW generally transmit the symbols via the packets, which results in the channel saturated especially for the large number of sensors access simultaneously. In order to address the channel saturated problem, sensor grouping is a promising solution by using the Binachi analysis approach for computing throughput and power consumption.

Specifically, let τ and p be the transmission probability and conditional collision probability, respectively. Based on Markove chain process, we first can derive the expression of transmission probability τ as:

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1) + pW_0(1-(2p)^m)}, \tag{2}$$

where W_0 is the size of the contention window, m denotes the maximum back-off stage. Intuitively, when each RAW contains multi-sensors, collision may emerge. Consequently, the condition collision probability p can be calculated as

$$p = 1 - (1-\tau)^{|g_j|-1}, \tag{3}$$

where $\left|g_j\right|$ is the number of the sensors of group g_j. It is noted that $m = 0$, which indicates that the exponential back-off stage can be ignored. In this case, the probability τ will be independent of p, so (2) is degraded into

$$\tau = \frac{2}{W_0+1}. \tag{4}$$

Accordingly, in a slot time, the probability P_j^t denoting no less than one sensor transmitting packet to AP, which can be given by

$$P_j^t = 1 - (1-\tau)^{|g_j|}. \tag{5}$$

Then the successful transmission probability P_j^s and collides probability P_j^c respectively can be calculated as

$$P_j^s = \frac{|g_j| \cdot \tau \cdot (1-\tau)^{|g_j|-1}}{P_j^t}, \tag{6}$$

$$P_j^c = 1 - P_j^s. \tag{7}$$

To formulate the EE over each group sensors, the traffic demands d_i generated by each sensor in type i are needed to be obtained during a beacon interval, that is,

$$d_i = L_i \cdot \lambda_i \cdot T_{\text{beacon}}, \tag{8}$$

where T_{beacon} is the duration of the beacon interval.

Generally, in the practical networks, the total length of packets is associated with the number of sensors and traffic demands, which is defined as

$$D_j(\boldsymbol{g}) = \sum_{i=1}^{M} T_{ij}(\boldsymbol{g}) d_i. \tag{9}$$

According to a grouping strategy $\boldsymbol{g}$ and expression (9), the total length of packets transmitted successfully by group g_j can be expressed by

$$D_j^s = D_j \cdot P_j^s. \tag{10}$$

Accordingly, the data rate of group g_j could be calculated as follow:

$$R_j(\boldsymbol{g}) = \frac{D_j \cdot P_j^s}{T_{\text{RAW}}}. \tag{11}$$

As a result, the energy consumption of group g_j can be given by

$$E_j^t = E_1 D_j P_j^s + E_2 D_j \left(1 - P_j^s\right) + E_{con} |g_j| T_{\text{RAW}}, \tag{12}$$

where E_1 is the energy consumption of successful transmission, E_2 denotes the energy consumption of collision that occurs in the assigned RAW slot, E_{con} is the contention power in one RAW slot, which is the energy consumption in wake-up mode.

From [12], it is seen that the energy consumption of transmitting overhead information in group g_j is corresponding to the number of RAW slots and sensors within one RAW. Thus, the energy consumption of overhead information in group g_j can be formulated as:

$$E_j^{head} = \frac{\alpha}{T_{\text{RAW}}/\sigma} \cdot \frac{\beta}{|g_j|}, \tag{13}$$

where α, β denote the parameter pointed to traffic and the total number of sensors, respectively; σ is the duration of Mini-slot.

When sensors with the number of $|g_j|$ attempt to access channel during jth RAW, the energy consumption of group g_j consists of transmission power and overhead information power can be given by

$$E_j(\boldsymbol{g}) = E_j^t + |g_j| E_j^{head}. \tag{14}$$

Based on derived (12), (13) and (14), the EE of group g_j could be defined as

$$\eta_j^{EE} = \frac{R_j(\boldsymbol{g})}{E_j(\boldsymbol{g})} = \frac{D_j P_j^s T_{\text{RAW}}}{D_j[E_1 P_j^s + E_2\left(1 - P_j^s\right)] + E_{con}|g_j| T_{\text{RAW}} + \frac{\alpha\beta\sigma}{T_{\text{RAW}}}}. \tag{15}$$

Note that in (15), since the variable D_j is integer, the formulated EE optimization problem is an integer nonlinear programming problem (INLP). Generally, INLP problem is usually transformed into non-integer linear programming (NILP) problem to solve it.

2)NINLP model construction: We assume that the number of sensors in each group is same, and the successful transmission probability P_j^s is a constant for the fixed $|g_j|$. In this case, we formulate it to maximize the minimum each senor group energy efficiency via sensor scheduling design under a large number of senors environment, $\mathcal{P}1$ can be rewritten as

$$\begin{aligned} \mathcal{P}\,2:\ & \max_{\boldsymbol{g}} \min_{j} \eta_j^{EE} \\ \text{s.t. } & \text{C1}: D = \sum_{j=1}^{K} D_j(\boldsymbol{g}), \\ & \text{C2}: D_j(\boldsymbol{g}) = \sum_{i=1}^{M} T_{ij}(\boldsymbol{g}) \cdot L_i \cdot \lambda_i \cdot T_{\text{beacon}}. \end{aligned} \tag{16}$$

Note that in (15), the objective function of $\mathcal{P}2$ includes many parameters. To simplify the problem, let $R_j = aD_j$, $E_j = bD_j + c$, where $a = P_j^S \big/ T_{RAW}$, $b = E_1 P_j^s + E_2\left(1 - P_j^s\right)$, $c = E_{con}|g_j| T_{RAW} + \alpha\beta\sigma \big/ T_{RAW}$ are all positive constants. According to the IEEE 802.11ah protocol, the traffic demands generated by group g_j is an integer, then $\mathcal{P}2$ is an INLP problem. Observing that R_j and E_j are discrete functions of D_j, which are also linear functions of D_j. We first drop the integer constraint C2 in (16). As a result, problem $\mathcal{P}2$ can be converted to the NINLP problem:

$$\begin{aligned} \mathcal{P}3:\ & \max_{\boldsymbol{g}} \min_{j} aD_j/(bD_j + c) \\ \text{s.t. } & \text{C1}: D = \sum_{j=1}^{K} D_j. \end{aligned} \tag{17}$$

It is obviously that the objective function of $\mathcal{P}3$ is concave, with the linear constraint C1. For fixed traffic demands, there exist multiple combinations of sensors. Therefore, it is difficult to obtain the optimal sensor grouping scheme. Thus, we will design a traffic grouping scheme in the following section.

III. OPTIMAL TRAFFIC GROUPING SCHEME ANALYSIS AND ALGORITHM DESIGN

According to the performance analysis in terms of EE under different sensor grouping scheme in previous section, we prove that the EE max-min fairness among all groups will be achieved for the same traffic demands of each group and further propose a traffic grouping algorithm by using the classic BBM approach to solve $\mathcal{P}2$ and realize the optimal traffic grouping.

A. NINLP MODEL TO MAX-MIN EE

Since different combinations of sensors can generate the same traffic demands, it is difficult to obtain optimal sensor grouping for problem $\mathcal{P}3$. Then we propose **Theorem 1** to find the optimal traffic grouping scheme. Due to the relationship of sensor grouping scheme and traffic grouping scheme, we can develop a traffic-sensor mapping algorithm to obtain a sensor grouping scheme to solve problem $\mathcal{P}2$.

Theorem 1: the optimal solution of (17) is obtained when the traffic demands generated by all sensors are distributed evenly among groups, i.e., $\boldsymbol{\mathcal{D}}^{\star} = [\bar{d}, \bar{d}, \ldots, \bar{d}]$, where $\bar{d} = D/K$.

Proof: Theorem 1 can be proven by using contradiction. For the fixed number of groups and sensors of each type. We assume that there exist the optimal traffic grouping scheme $\boldsymbol{\mathcal{D}}^{\star} = [D_1, D_2, \ldots, D_K]$ of $\mathcal{P}3$, which satisfy the uneven traffic distribution of all groups. We assume group g_i has the lowest EE, i.e., $\eta_i^{EE} = \min \eta_j^{EE}, j \in \mathcal{K}$. We then calculate the first derivative of the objective function of (17) as follow:

$$\eta_j^{EE}(D_j)' = \frac{ac}{(bD_j + c)^2}. \tag{18}$$

Since $a, b, c > 0$, $\eta_j^{EE}(D_j)' > 0$, which means the EE of group g_j increases with respect to different traffic demands. Therefore, D_i is the lowest traffic demands in all groups. Because the traffic demands of each group is randomly distributed, then $D_i < \bar{d} = \frac{D}{K}$ and $\eta_i^{EE}(D_i) < \eta_i^{EE}(\bar{d})$. It implies that there exist one solution $\boldsymbol{\mathcal{D}} = [\bar{d}, \bar{d}, \ldots, \bar{d}]$ to make the objective value $\mathcal{P}3(\boldsymbol{\mathcal{D}}) > \mathcal{P}3(\boldsymbol{\mathcal{D}}^{\star})$. Therefore, the assumed optimal solution $\boldsymbol{\mathcal{D}}^{\star}$ is not optimal, which violates the hypothesis. ■

Note that $\bar{d}$ could be regarded as the mean value of the traffic demands, which might not be an integer. In this subsection, by dropping the non-convex integer constraint C2 in problem $\mathcal{P}2$, we relaxed problem $\mathcal{P}2$ into the convex problem $\mathcal{P}3$ and use BBM to solve such integer programming problem $\mathcal{P}3$ [37]–[39]. Next, we need to design a novel algorithm to make the solution of $\mathcal{P}3$ meet the optimization problem $\mathcal{P}2$.

B. DESIGNING OF THE TRAFFIC GROUPING ALGORITHM (OTGA)

To solve problem $\mathcal{P}2$, we first design a traffic grouping algorithm based on BBM, and find the optimal traffic grouping solution $\boldsymbol{\mathcal{D}}^{\star}$. The lower and upper bound of the optimal solution of $\mathcal{P}2$ are denoted by $\mathcal{D}_{\text{LB}}$ and $\mathcal{D}_{\text{UB}}$ respectively. The idea of BBM is to decrease $\mathcal{D}_{\text{UB}}$ and increase $\mathcal{D}_{\text{LB}}$ gradually

Algorithm 1 OTGA

Input: the number of groups K, the traffic demands generated by all sensors D.

Output: the optimal traffic grouping solution $\boldsymbol{\mathcal{D}}^{\star}$.

1: $i = 1, \bar{d} = \frac{D}{K}, \mathcal{D}_{\text{LB}} = [1, \cdots, 1], \mathcal{D}_{\text{UB}} = \left[\bar{d}, \cdots, \bar{d}\right]$
2: **while** $i \leq K$ **do**
3: $\quad \forall e, i, j, o \in \{1, \cdots, K\}, e < i < j, m = \{l, u\}$;
4: $\quad D_e^m = D_e, D_i^m = \{\lfloor \bar{d} \rfloor, \lceil \bar{d} \rceil\}, D_j^m = \frac{D - \sum_{o \leq i} D_o^m}{K - i}$;
5: $\quad \mathcal{D}^m = [D_1^m, \cdots, D_K^m]$;
6: $\quad$ **if** both $\mathcal{D}^l, \mathcal{D}^u$ are feasible **then**
7: $\quad\quad \mathcal{D}^{\star} = \arg\max\min\left\{\eta(\mathcal{D}^l), \eta(\mathcal{D}^u)\right\}$;
8: $\quad\quad EE^{\star} = \eta(\mathcal{D}^{\star}), \mathcal{D}_{\text{LB}} = \mathcal{D}^{\star}$;
9: $\quad\quad$ go to 28;
10: $\quad$ **else if** $\mathcal{D}^l$ or $\mathcal{D}^u$ is feasible **then**
11: $\quad\quad$ set the feasible and infeasible scheme as $\mathcal{D}_1$ and $\mathcal{D}_2$ respectively;
12: $\quad\quad$ **if** $D_1 = \arg\max\min\{\eta(D_1), \eta(D_2)\}$ **then**
13: $\quad\quad\quad \mathcal{D}^{\star} = \mathcal{D}_1, EE^{\star} = \eta(\mathcal{D}_1), \mathcal{D}_{\text{LB}} = \mathcal{D}_1$;
14: $\quad\quad\quad$ go to 25;
15: $\quad\quad$ **else**
16: $\quad\quad\quad \mathcal{D} = \mathcal{D}_2, \mathcal{D}_{\text{LB}} = \mathcal{D}_1, \mathcal{D}_{\text{UB}} = \mathcal{D}_2$;
17: $\quad\quad$ **end if**
18: $\quad$ **else**
19: $\quad\quad \mathcal{D} = \arg\max\min\{\eta(\mathcal{D}^l), \eta(\mathcal{D}^u)\}, \mathcal{D}_{\text{UB}} = \mathcal{D}$;
20: $\quad$ **end if**
21: $\quad$ set the i^{th} and j^{th} element in $\mathcal{D}$ as D_i and D_j respectively;
22: $\quad \bar{d} = D_j, \forall i, j \in \{1, \cdots, K\}, i < j$;
23: $\quad i = i + 1$;
24: **end while**

through keeping branch the non-integer grouping, in this way, the maximum $\mathcal{D}_{\text{LB}}$ can be got eventually, which is equal to the maximal EE of the minimum group. The detail procedure is summarized in Algorithm 1. In Algorithm 1, steps 4-5 present two branches of traffic grouping scheme. In steps 7-22, let the objective value of the feasible branch denote the new lower bound for two branches. If the objective value of an infeasible solution is higher than the one of feasible branch, it will be the new upper bound. Sequentially, we continue to branch the infeasible solution until the solution of the optimal traffic grouping is found. We summarize Algorithm 1 as follows:

Step 1: Initialization.

steps 2-5 present two branches of of variable $\mathcal{D}$ by adding the constraints $D_i \leq \lfloor \bar{d} \rfloor$ and $D_i \geq \lceil \bar{d} \rceil$ to $\mathcal{P}2$, respectively.

Steps 6-26, examine the feasibility of each branch to see whether it satisfy the constraints C1 and C2 in $\mathcal{P}2$. Let the objective value of the feasible branch denote the new lower bound for two branches. If the objective value of an infeasible solution is higher than the one of feasible branch, it will be the new upper bound. Sequentially, we continue to branch the infeasible solution until the optimal solution of the traffic grouping $\boldsymbol{\mathcal{D}}^{\star}$ is found.

Based on algorithm 1, we can get the optimal solution of traffic grouping scheme, given that different combinations of sensors can get the same traffic demands, it is difficult to search for the optimal solution of sensor grouping scheme. Next, we propose a heuristic traffic-user mapping algorithm to achieve a sub-optimal performance in terms of minimum energy efficiency among groups. Algorithm 1 is based on BBM, which needs to cycle K times to judge the traffic demands of each group. The computational complexity of finding the optimal solution is $O(K)$.

IV. DESIGNING OF TRAFFIC-SENSOR MAPPING ALGORITHM

In the previous section, we propose an optimal traffic grouping algorithm to maximize the EE of the worst group. However, considering that different combinations of M types of sensors can get the same traffic demands, it is difficult to obtain the optimal sensor grouping scheme from Algorithm 1. To overcome the challenge problem, we develop a heuristic traffic-sensor mapping algorithm to get a sub-optimal sensor grouping scheme.

A. HEURISTIC TRAFFIC-SENSOR MAPPING ALGORITHM (HTMA)

Though the optimal traffic grouping solution has been obtained in Algorithm 1, combining the multiple types of sensors is still a challenging problem. This is because that different combinations of multiple types of sensors can get the same traffic demands. Regarding to a fixed traffic demand, there may be multiple combination of sensors that can satisfy it. Thus, we propose a heuristic algorithm to find the traffic-sensor mapping scheme which can achieve a the sub-optimal solution of $\mathcal{P}2$.

In order to simplify the description of our proposed heuristic algorithm, we assume that the traffic demands generated by each type of sensors is in ascending order, i.e., $d_1 < d_2 < \cdots < d_M$. For each type of sensors are distributed evenly over the beacon periods with average $|T_i|/K$, $i \in \mathcal{M} = \{1, 2, \ldots, M\}$, denoted as $O_i + P_i$, where O_i is an integer and $0 \leq P_i < 1$.

Algorithm 2 consists of two main blocks: i) sensors of each type can be evenly divided into K groups simultaneously (lines 3-8), ii) exist one or more types of sensors cannot be divided into K groups equally (lines 9-23). Algorithm 2 can be described in detail as follow:

Firstly, if sensors of type M can be divided into K groups equally, each group is assigned T_M/K sensors of type M (lines 3-4). In this case, if sensors of type M can be divided into K groups equally, let O_{M-1} sensors of type $M-1$ join in each group (lines 5-6), if sensors of type $M-2$ can be divided into K groups equally, and the same as sensors of type $M-3$, put T_{M-2}/K and T_{M-3}/K sensors into each group (lines 7-8) respectively.

In the second case (lines 9-32), the arrangement of four types of sensors should discuss classification.

If the number of sensors of type $M-1$ cannot be divided uniformly, the first P_{M-1} groups have $O_{M-1}+1$ sensors of type $M-1$ and the following $K-P_{M-1}$ groups have O_{M-1} sensors of type $M-1$ (lines 15-16), so the first P_{M-1} groups have one more sensor per group than the follow groups, then if the number of sensors of type $M-2$ is less than $K-P_{M-1}$, add one sensor of type 2 to the group from $g_{P_{M-1}+1}$ to $g_{P_{M-1}+1+T_{M-2}}$, else put one sensor of type 2 to the following $K-P_{M-1}$ groups (lines 17-20), then go to back the line 7 to judge if sensors of type 2 remained can be evenly divided among K groups; if the number of sensors of type $M-1$ cannot be divided averagely, the first P_M groups have O_M+1 sensors of type M and the following $K-P_M$ groups have O_M sensors of type $M-1$ (lines 25-26), so the first P_M groups have one more sensor per group than the follow groups, then if the number of sensors of type $M-1$ is less than $K-P_M$, add one sensor of type $M-1$ to the group from g_{P_M+1} to $g_{P_M+1+T_{M-1}}$, else put one sensor of type $M-1$ to the following $K-P_M$ groups (lines 27-30), then go to back the line 5 to judge if sensors of type $M-1$ remained can be evenly divided among K groups. Since we consider a scenario where the number of nodes in each group is equal, if these three types of sensors have been divided already, then sensors of type $M-3$ in each group could be obtained directly (line 33).

Based on algorithm 2, if the number of sensors of four types is fixed, we can obtain the number of groups and sensor grouping scheme, and it is easy to allocate sensors to groups based on the output of HTMA. Algorithm 2 consisting two step: For any given number of groups K and the number of sensors of each type T_i, $i \in \{1, 2, \cdots, M\}$, we first need to judge whether the number of sensors of each type can be divisible by K, then each group is assigned each type of sensors according to the judgment result, so the computational complexity is $O(M \times K)$.

V. SIMULATION RESULTS

In this section, simulations results are presented to evaluate the effectiveness of the proposed energy-efficient sensor grouping scheme based on traffic distribution. We consider four types of sensors and corresponding traffic patterns, which are shown in Table 1. Simulation parameters are presented in Table 2. The following schemes are compared:

- **Scheme 1** (HTMA: heuristic traffic-sensor mapping algorithm): The proposed sensor grouping scheme in Algorithm 2.
- **Scheme 2** (GA: greedy algorithm): For each group, sensors with heavy traffic demands have priority join current group.
- **Scheme 3** (RA: random algorithm): For each sensor, it chooses a group randomly and transmits packets in its chosen slot.
- **Scheme 4** (Retransmit: retransmit algorithm in [13]): For each sensor, it selects any RAW slot with equal probability, if it collides in its assigned RAW, they can retransmit their packets once again in next RAW slot.

Algorithm 2 HTMA

Input: the number of sensors of type $i, T_i, i \in \{1, 2, \cdots, M\}$, the number of groups K.

traffic-sensor

Output: mapping scheme $\boldsymbol{g}^*$, energy efficiency of minimum group $\boldsymbol{EE}^*$.

$T_{i,j} = 0, T_i/K = O_i + P_i, O_i \in Z, P_i \in [0, 1)$;
2: $i = 1, j = 1, \forall j, k \in \{1, \cdots, K\}, j < k$;
if $P_M = 0$ **then**
4: $T_{M,j} = O_M, j \in \{1, 2, \cdots, K\}$;
if $P_{M-1} = 0$ **then**
6: $T_{M-1,j} = O_{M-1}, j \in \{1, 2, \cdots, K\}$;
if $P_{M-2} = 0$ **then**
8: $T_{M-2,j} = O_{M-2}, j \in \{1, 2, \cdots, K\}$;
else
10: $T_{M-2,j} = O_{M-2} + 1, j \in \{1, \ldots, P_{M-2}\}$;
$T_{M-2,k} = O_{M-2}, k \in \{P_{M-2} + 1, \ldots, K\}$;
12: go to 35;
end if
14: **else**
$T_{M-1,j} = O_{M-1} + 1, j \in \{1, \ldots, P_{M-1}\}$;
16: $T_{M-1,k} = O_{M-1}, k \in \{P_{M-1} + 1, \ldots, K\}$;
if $T_{M-2} \leq K - P_{M-1}$ **then**
18: $T_{M-2,k} = 1, k \in \{P_{M-1} + 1, \ldots, P_{M-1} + 1 + T_{M-2}\}$;
else
20: $T_{M-2,j} = 1, k \in \{P_{M-1} + 1, \ldots, K\}$;
end if
22: go to 7;
end if
24: **else**
$T_{M,j} = O_4 + 1, j \in \{1, \ldots, P_M\}$;
26: $T_{M,k} = O_4, k \in \{P_M + 1, \ldots, K\}$;
if $T_{M-1} \leq K - P_M$ **then**
28: $T_{M-1,k} = 1, k \in \{P_M + 1, \ldots, P_M + T_{M-1}\}$;
else
30: $T_{M-1,j} = 1, k \in \{P_M + 1, \ldots, K\}$
end if
32: go to 5;
end if
34: $\vdots$
$T_{1j} = \left(\sum_{i=1}^{M} T_i\right)/K - \sum_{i=2}^{M} T_{ij}, j \in \{1, 2, \cdots, K\}$;
36: Output traffic-sensor mapping scheme $\boldsymbol{g}^\star$, energy efficiency of minimum group $\boldsymbol{EE}^\star$.

Fig. 2 shows the total EE versus the number of sensors for analysis and simulation with the proportion of four types of sensors $\alpha = 0$, i.e., each traffic pattern is assigned 25% of sensors. It is revealed that our analysis model accurately predict the EE.

Fig. 3 shows the total EE versus the number of sensors for OTGA and HTMA theoretically. It is seen that the proposed HTMA grouping scheme obtains a close-form solution of

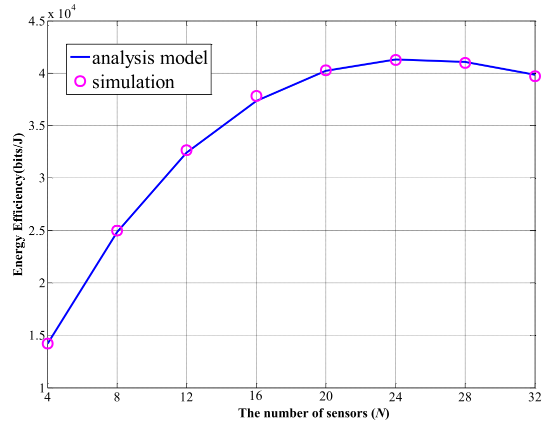

FIGURE 2. Energy efficiency Comparison between Analysis and Simulation.

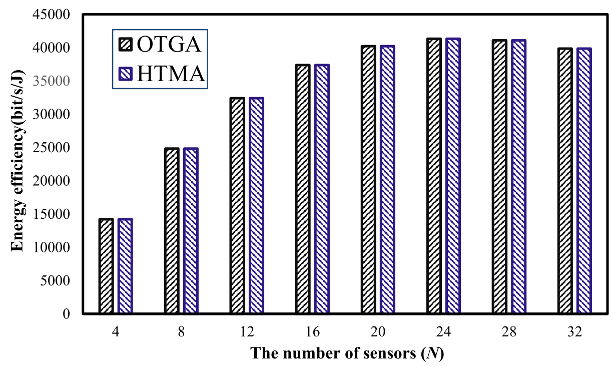

FIGURE 3. Energy efficiency Comparison between OTGA and HTMA.

TABLE 1. Four types of traffic patterns.

	Type 1	Type 2	Type 3	Type 4
Packet length	256 Bytes	256 Bytes	256 Bytes	256 Bytes
Sampling rate	2 Hz	4 Hz	6 Hz	8 Hz
Proportion	$25 - 2\alpha$	$25 - \alpha$	$25+\alpha$	$25+2\alpha$

optimal EE. This is because the traffic demands generated by each group under the two schemes is nearly close. Moreover, we observed that the EE increases first and decreases then with N. The promotion is mainly caused by the total traffic demands increase with N for a fixed RAW duration. However, the successful transmission probability decreases with respect to different N. As a result, the total data rate will decrease when the number of sensors increases to a certain level, and the total energy consumption always decreases as the number of sensors increases.

Fig. 4 shows the EE of the network and each group for different schemes, where the number of sensors and groups are set to 16 and 4 respectively. It is observed that the proposed HTMA grouping scheme guarantees the EE fairness among groups and outperforms the other schemes. This is because the HTMA grouping scheme ensure the EE of each group with some sacrifice in the network EE. While, the GA grouping scheme aims to pursue EE of current group and exists

TABLE 2. Summary of the simulation parameters values.

Parameter	Value
Beacon duration (T_{beacon})	500 ms
Slot time (σ)	9 us
Initial contention window	16
α	200
β	200
Data rate(r_i)	100 Mbps
Transmission power per bit (E_1)	2/1024 mw/bit
Collision power per bit (E_2)	3/1024 mw/bit
Idle listen power (E_{con})	0.001 mw

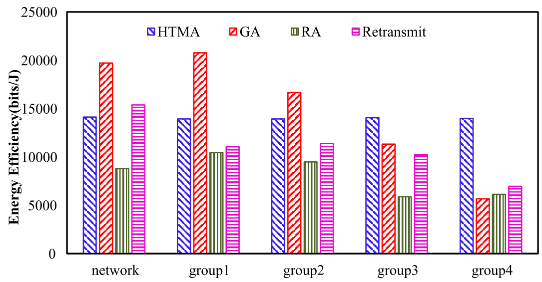

FIGURE 4. Energy efficiency of the network and each group for various grouping schemes under $K = 4$, $N = 16$ and $\alpha = 0$.

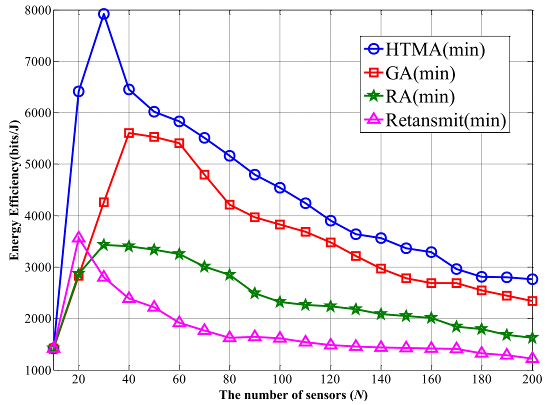

FIGURE 5. The minimum energy efficiency among groups for various schemes when the number of sensors changes.

unfairness among groups due to different traffic demands distribution. The RA grouping scheme leads to different collision probabilities among groups. The retransmit grouping scheme in [10] will result in more intense collision within some groups.

Fig. 5 illustrates the minimum EE among groups versus the number of sensors for various schemes by assuming that the proportion of four types of sensors α and the number of groups are 0 and 10 respectively. We observe that the HTMA scheme has the higher performance in terms of the minimum EE among groups than other schemes, for which the gain is mainly attributed to the balanced traffic demands. Furthermore, it is observed that the minimum EE among groups increases first and then decreases with the number of sensors. This is because as the number of sensors increases, the data rate increases due to the traffic demands increases

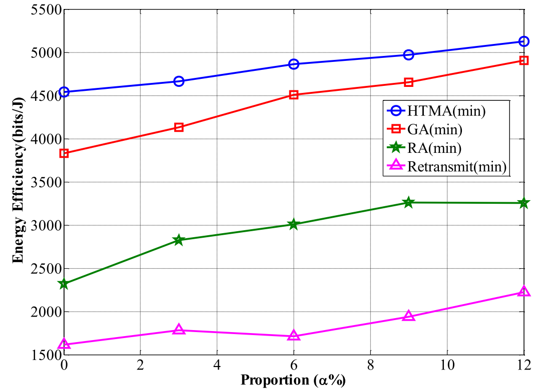

FIGURE 6. The minimum energy efficiency of a group with heterogeneous traffic demands when $N = 100$, $K = 10$.

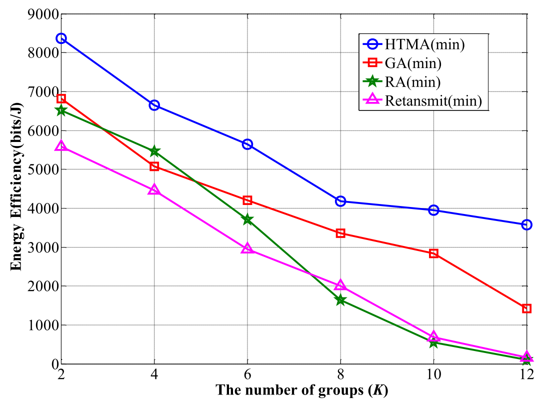

FIGURE 7. The minimum energy efficiency among groups with respect to different number of groups K, when $N = 120$, $\alpha = 0$.

at first, and the energy consumption also increases caused by collision probability increased. However, the data rate increases more than the energy consumption. When the number of sensors increases to a certain level, the competition intensifies resulting in the decrease of data rate.

Fig. 6 shows the minimum EE among groups for different grouping schemes with the number of sensors $N = 100$, and all sensors are divided into 10 groups. As can be seen, the minimum EE of a group increases with the proportion of four types of sensors. This is expected since the total traffic demands increase with α. Moreover, it is clearly found that the HTMA achieves a higher EE of worst group than other grouping schemes. This is because when α increases, the proposed algorithm can distributed traffic evenly among groups and ensures that the contention level is almost the same among groups. Thus, our proposed grouping strategy is more suitable for heterogeneous networks.

Fig. 7 presents the minimum EE among groups versus the number of groups, where the number of sensors and the proportion of four types of sensors are set as 100 and 0 respectively. The results show that the minimum EE of a group in other schemes decreases quickly when the number of groups increases, for which the attenuation is mainly caused

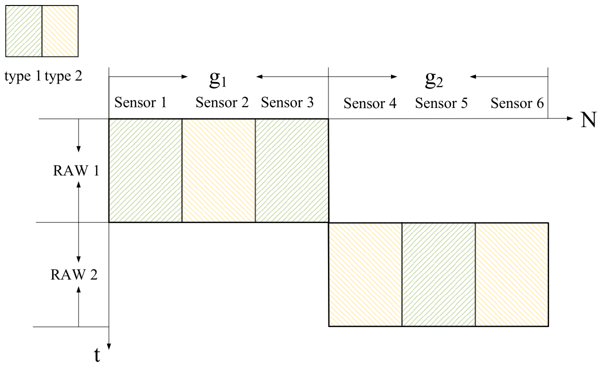

FIGURE 8. A toy for sensor grouping scheme.

by different congestion level among groups. It is revealed that improper sensor grouping strategy may cause the congestion severe in some groups and make some sensors starve. The proposed sensor grouping strategy based on traffic distribution can ensure that the congestion level of each sensor group is basically the same, which brings about an improvement in the performance in terms of the worst group.

VI. CONCLUSION

In this paper, we investigated sensor grouping based max-min EE problem for the IEEE 802.11ah networks to improve the minimum EE among groups. The formulated problem is an integer nonlinear programming (INLP) model. In particular, we observed that the minimum EE among groups is maximized when the traffic demands are distributed evenly among all groups. Based on this observation, we proposed an optimal traffic grouping algorithm (OTGA) based BBM to solve INLP problem and obtain an optimal solution of traffic grouping scheme. For the proposed traffic grouping algorithm, we can obtain the traffic demands of each group. Different combinations of sensors can generate the same traffic demands, thus, it is difficult to get the sensor grouping scheme from the proposed scheme. Furthermore, we presented a heuristic traffic-sensor mapping algorithm (HTMA) for a sub-optimal solution of sensor grouping scheme. The theoretical and simulation results showed that the HTMA scheme achieves the sub-optimal EE and guarantees the EE with the max-min fairness among groups.

APPENDIX

A TOY OF GROUPING SCHEME

Assume that the network contains 6 sensors, and these sensors are divided into 2 groups, denoted as g_1 and g_2.

Sensors in group g_1: $\mathcal{G}_1 = \{1, 2, 3\}$.

Sensors in group g_2: $\mathcal{G}_1 = \{4, 5, 6\}$.

So the six sensors can be labeled as type 1 and type 2.

The set of sensors of type 1: $\mathcal{T}_1 = \{1, 3, 5\}$, each of which generates d_1 bit packets in one beacon interval.

The set of sensors of type 2: $\mathcal{T}_2 = \{2, 4, 6\}$, each of which generates d_2 bit packets in one beacon interval.

Sensors of type 1 in group g_1: $\mathcal{T}_{11} = \{1, 3\}$.

Sensors of type 1 in group g_2: $\mathcal{T}_{12} = \{5\}$.

Sensors of type 2 in group g_1: $\mathcal{T}_{21} = \{2\}$.

Sensors of type 2 in group g_2: $\mathcal{T}_{22} = \{4, 6\}$.

Traffic demands generated by sensors of group g_1: $\mathcal{D}_1 = \{d_1, d_2, d_1\}$, the total traffic demands of group g_1 is $D_1 = 2d_1 + d_2$.

Traffic demands generated by sensors of group g_2: $\mathcal{D}_2 = \{d_2, d_1, d_2\}$, the total traffic demands of group g_2 is $D_2 = d_1 + 2d_2$.

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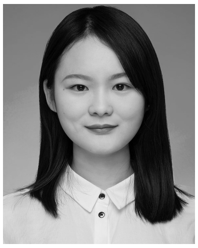

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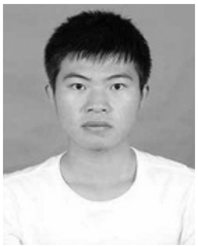

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