A Dominating Set-Based Sleep Scheduling in Energy Harvesting WBANs

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***Abstract*—Energy Harvesting Wireless Body Area Networks (EH-WBANs) where sensor nodes can harvest energy from their ambient environment are of great potential for low-power medical monitoring systems. The availability of energy in EH-WBANs, however, is challenged by uncertainty of harvested energy sources and limited charging efficiency, and thus the energy saving is still of great importance. To improve energy efficiency, this paper studies the sleep scheduling problem in EH-WBANs, which is of fundamental importance for network lifetime and connectivity while being not systematically addressed. Technically, this problem is proved to be NP-Complete, and thus needs non-trivial efforts to deal with. To that end, we present a series of approximation algorithms with proven performance from perspective of constructing minimum dominating set (DS), where energy saving and energy harvesting techniques are combined to prolong the network lifetime while guaranteeing real-time requirement of EH-WBANs. Specifically, we first propose a centralized algorithm that can construct DS with minimum size and discover the maximum number of DSs. We then design two distributed algorithms independent of prior global knowledge to improve network scalability, namely EEU and Improved EEU respectively. Theoretical analysis and extensive simulations are conducted to confirm the superiority of the proposed sleep scheduling algorithms.**

***Index Terms*—Body area networks, sleep scheduling, energy harvesting.**

I. Introduction

WIRELESS Body Area Networks (WBANs) that are able to offer a variety of potential medical applications are very popular as an Internet of Things (IoT) healthcare system in recent years [1] [2]. By deploying wireless tiny sensor nodes around, on or implanted in the human body, the physician can obtain long-term physiological parameters of patients so that many diseases can be detected in nearly real time and correctly treated. There, however, exist several challenges hindering longer-term operations of WBANs. The fundamental one is the limited network lifetime resulted from scarce battery capacity of sensor nodes [3]. Therefore, many research efforts have been devoted to prolonging the network lifetime, which can be classified into two categories: energy saving strategy and energy harvesting strategy.

In energy saving strategy, the duty cycling technique has been extensively regarded as the most energy-efficient one [4]. This enables each sensor node switches between active and sleep states. Sensor nodes can transmit or receive data only in the active state, while most of functional modules are turned off in the sleep state in order to save energy. Recently, with widespread applications of rechargeable batteries, energy harvesting technique attracts much attention for its ability of prolonging network time, where sensor nodes can automatically harvest energy from their ambient environment such as sun light, thermal energy, radio signals, body movement and vibration [5]. Energy Harvesting WBANs (EH-WBANs) are thus promising for long-term medical monitoring applications.

Yet the two strategies have inherent limitations. First, duty cycling technique leads to network intermission and thus suffers from severe transmission delay as sensor nodes generally have different duty cycling periods in WBANs and it is difficult to ensure their simultaneous activation. While the real-time physiological data is vital to make diagnosis in medical applications. Therefore, how to schedule sensor nodes between active and sleep states to prolong the network lifetime while guaranteeing the connectivity and delay requirement is very important for WBANs. Second, the available energy of sensor nodes is finite even equipping with energy harvesting capacity due to interruption of harvested energy sources like solar power at night and limited charging efficiency. How to tackle the limitations, however, is still an open issue.

In order to bridge this gap, we combine the energy saving and energy harvesting strategies to maximize the network lifetime while reducing transmission delay. Specifically, we try to schedule the minimum sensor nodes to relay packets from the other active nodes to ensure the network connectivity, which can be formulated as the problem of constructing Dominating Set (DS) and is proven time-efficient for EH-WBANs. The key challenge lies in that the number of DSs also affects network lifetime in addition to size of a DS, which is resulted from introduction of energy harvest. And they are intertwined, making the sleep scheduling problem more difficult in EH-WBANs (cf. Section VI for related work). To our best knowledge, there is

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no other work to investigate this issue for EH-WBANs theoretically. The main contributions of this paper can be articulated as follows:

- First, we formulate a novel sleep scheduling problem aiming at finding the maximum number of DSs in an EH-WBAN, which is further proven to be NP-Complete and is thus very challenging.
- Second, a centralized algorithm is proposed to address the NP-Complete problem and its performance is analyzed theoretically giving an approximation ratio of $1 + \ln \Delta$ where Δ is the maximum node degree.
- Third, we design a distributed algorithm with constant computational complexity and communication overhead, achieving dominating set-based sleep scheduling without a prior global knowledge and improving the network scalability. An improved one is further designed with the prior cost reduced by one third. They enable distributed implementation of the sleep scheduling in EH-WBAN, and provide tradeoff between network lifetime and computational complexity.
- Extensive simulations are conducted to evaluate the algorithm performance. The simulation results demonstrate the efficiency of our algorithms in prolonging network lifetime, and confirm the analytical results.

II. Network Model and Problem Formulation

In this section, we introduce the energy harvesting network model and formulate the sleep scheduling problem in EH-WBANs from the perspective of constructing DSs.

A. Network Model

We consider a time-slotted duty cycling and energy harvesting WBAN that consists of one sink and N sensor nodes. The sink is usually assumed to have an unlimited and uninterrupted power supply and be always active, while the sensor nodes are deployed on the appropriate locations of human body based on their individual functionalities, e.g., monitoring the corresponding physiological parameters. The sink then collects data from sensor nodes and transmits them to users via an external gateway. As specified in IEEE 802.15.6 standard [6], each sensor node can communicate with the sink in two hops via a relay node in order to improve the reliability. As a result, given a time slot, we should ensure the reliability that sleep nodes have at least one active neighbor when partial sensor nodes are scheduled to work while the others turn to sleep for energy saving and harvesting. Meanwhile, the network connectivity should also be guaranteed for nearly real-time communications in duty cycling EH-WBAN. To that end, we schedule sensor nodes to form DSs each working as backbone.

Given a graph $G = (V, E)$ to denote an EH-WBAN, where $V = \{1, 2, \ldots, N\}$ is the set of sensor nodes and E is the set of edges implying the neighborhood relationship among sensor nodes. A subset $D \subseteq V$ is a **DS** if and only if any $v \in (V - D)$ is adjacent to at least one node in D. The nodes in DS are called **dominators**, while the others are called **dominatees**. At each slot, the dominators work while the dominatees switch to sleep state when they can harvest energy. Each node has a single antenna, so it cannot harvest energy while sending data. We next illustrate the sleep scheduling in an EH-WBAN of one sink and 11 sensor nodes through DS construction in Fig. 1. The set {2, 4, 8} of nodes is a DS able to work for one slot while the left ones go to sleep to save and harvest energy as shown in Fig. 1(a). Similarly, nodes {3, 6, 10} in Fig. 1(b) construct a new DS for another slot.

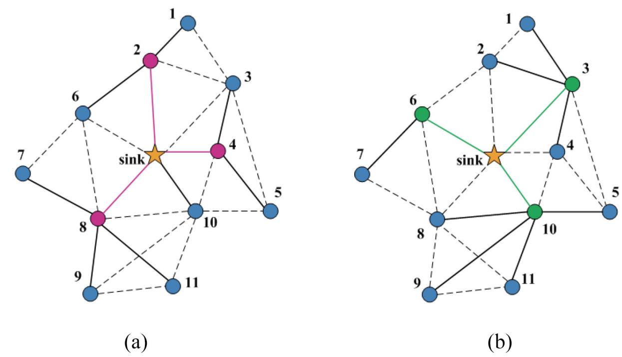

Fig. 1. Two examples of constructing DSs in an EH-WBAN: nodes {2, 4, 8} construct a DS in (a); nodes {3, 6, 10} construct another DS in (b).

Without loss of generality, we define the work period of a sensor node as the time interval from when it starts working to when its energy is depleted. Obviously, the lifetime of a DS is decided by the minimum work period among all sensor nodes in the same DS. In an EH-WBAN, we could construct such multiple DSs that a fresh DS can be scheduled to work slot after slot and the network can still operate even if some sensor nodes ran out of their energy. We formally define the *network lifetime* of an EH-WBAN as follows:

Definition 1 (Network Lifetime): Let T_b be the time slot that the network G begins to work and T_r be the time slot when there does not exist any DS to work in G, the network lifetime is $T = T_r - T_b$.

We would like to emphasize that the network lifetime in this paper means the duration from the initiation of the network to the transmission interrupt from all nodes to the sink either for the energy exhaustion or the lack of relay nodes.

B. Problem Formulation

In order to prolong the network lifetime and ensure the real-time requirement of EH-WBANs, this paper designs sleep scheduling algorithms by constructing one DS for each time slot. Let DS_i and DS_j denote the DSs of an EH-WBAN G working in the i-th and j-th time slot, respectively. Note that the sensor nodes in DS_i and DS_j may overlap. Discovering the maximum number of DSs that can work in different time slots can considerably prolong the network lifetime.

Consider the EH-WBAN $G(V, E)$, the initial energy of sensor node v is defined as $w_v(0)$. Sensor nodes are assumed to consume a constant amount of energy ε when it is active and transmits data, and the energy harvesting rate of each one is δ per slot. Let $S_{DS} = \{DS_1, DS_2, \ldots, DS_k\}$ define DS set where $|S_{DS}|$ is the cardinality of DS set, the sleep scheduling problem

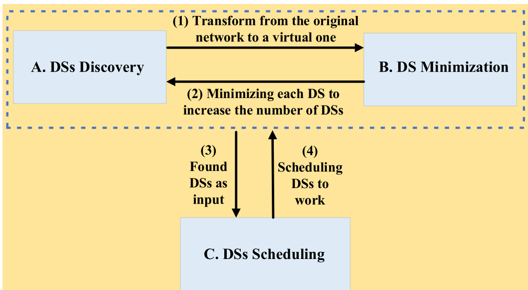

Fig. 2. The process of the proposed centralized scheme.

for an EH-WBAN can be formulated as:

$$\begin{aligned} \text{Objective:} \quad & \max |S_{DS}| \\ \text{Subject to} \quad & w_v(i) > \epsilon \\ & v \in DS_i, \text{where } 1 \leq i \leq k. \end{aligned} \tag{1}$$

We would like to emphasize that the problem in an EH-WBAN is quite different from and more challenging than that in a traditional WBAN. The reason lies in that energy harvest introduces another dimension to this problem in addition to neighborhood relationship and energy consumption. Let us take Fig. 1 as an example where the initial energy of each sensor node is set to 5 units, the energy consumption of each dominator is 1 unit per time slot and each dominatee can harvest 0.5 unit energy per time slot. Consider a traditional WBAN, the maximum number of time slots that the DSs can work is 10, i.e., the network lifetime is 10 at most, yet it can be extended to 18 by constructing and scheduling DSs in an EH-WBAN where dominatees can harvest energy during sleep. After further dissecting this problem, we find it NP-Complete, which is formally stated below.

Theorem 1: The formulated sleep scheduling problem (1) in an EH-WBAN is NP-Complete.

Proof: Let $\delta = 0$, i.e., each sensor node cannot harvest energy, the sleep scheduling problem degrades to the Domatic Number (DN) problem which has been proved to be NP-Complete in [7]. Therefore, the sleep scheduling problem in an EH-WBAN is also NP-Complete. ■

Consider the complexity of NP-Complete problem, we would design approximation algorithms approaching the optimal solution. In what follows, we will first present a centralized scheme, and propose two schemes with lower computational complexity in sequence for distributed implementation.

III. A Centralized Solution

In this section, we elaborate a centralized scheme to address the sleep scheduling problem in EH-WBANs. The scheme consists of three parts each answering one of the following three questions in sequence.

1) How to maximize the number of DSs in an EH-WBAN?
2) How to minimize the size of one DS?
3) How to schedule the discovered DSs to prolong the network lifetime to the most extent?

As shown in Fig. 2, we first construct a virtual network from the original one and verify the feasibility of this transform. We then design an algorithm to find minimum DS, which would make more DSs available. After finding all DSs, we execute the scheduling method to have dominators to work.

A. Discovering DSs

With energy harvesting technique, sensor nodes in EH-WBANs can have external energy supply, and the residual energy may increase instead of monotonously decreasing with time. This nonmonotonous residual energy makes the sleep scheduling problem more difficult. For analysis tractable, we introduce a new concept named *virtual network* that can represent the energy and neighbor relationships of the original network together. The rule of constructing virtual network is stated as follows: each node of the original network, called *ancestor*, is converted into multiple mutually connected *Virtual Nodes* (VNs) in the virtual network. These VNs of the same ancestor are indexed and formed a *Virtual Group* (VG), where the number of VNs depends on the energy of their ancestor. The VNs in the same VG are completely connected with each other, and they connect with each VN of other VGs if their ancestors are connected in the original network. Consequently, an original network can be replaced by a virtual network.

Following the concept of virtual network, we introduce the three-step centralized scheme similar to [8] to transform the problem in the original graph to the virtual one by three steps:

- Step I: We need to evaluate the maximum number of VNs for each ancestor in the original network, i.e., the maximum number of time slots that each sensor can work.
- Step II: A corresponding virtual network G' is built based on the original network G. Seeking the maximum number of DSs in EH-WBNAs can thus be transformed to finding the maximum number of disjoint DSs in the virtual network. To this end, we design a new minimum DS discovery algorithm.
- Step III: The disjoint DSs in Step II are converted to the solution of the original problem in EH-WBANs.

We next elaborate each step and analyse the effectiveness and efficiency of the algorithm theoretically.

Step I: Let f_v denote the number of DSs that sensor node v belongs to, in other words, node v could work as a dominator for f_v time slots. The following theorem implies the upper bound of f_v, where $1 \leq v \leq N$.

Lemma 1: Given the initial energy $w_v(0)$ of node v, the energy consumption rate ε and the rechargeable rate δ in an EH-WBAN, let $N(v)$ denote the neighbors of node v, the number of DSs f_v where node v can work as a dominator is upper bounded by $\lfloor \frac{\varepsilon w_v(0)+\delta \sum_{q\in N(v)} w_q(0)}{\varepsilon^2} \rfloor$.

Proof: For any node v and DS_i, let $I_{v,i}$ be an variable indicating whether node v belongs to DS_i or not, that is

$$I_{v,i} = \begin{cases} 1 & \text{if } v \in DS_i \\ 0 & \text{if } v \notin DS_i \end{cases}.$$

According to the property of DS, if $v \notin DS_i$, then there exists at least one of its neighbors belonging to DS_i. It thus holds that $\sum_{q\in N(v)} I_{q,i} \geq 1$.

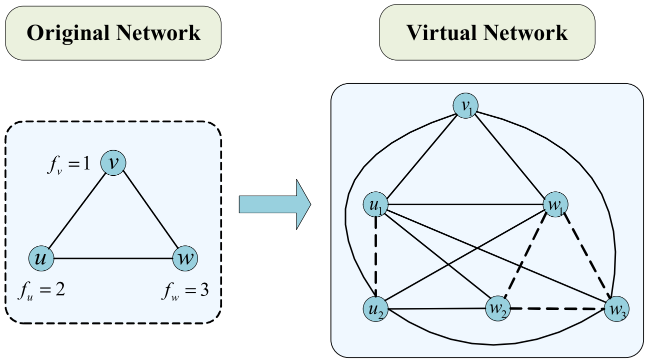

Fig. 3. The construction of a virtual network: The dash lines denote the edges in the same VG. The solid lines represent the edges among different VGs.

In an EH-WBAN, if one node is scheduled to keep active in a given time slot, its sleeping neighbors can charge for a time slot through energy harvesting technique. Let c_v denote the number of time slots when node v is charging. The total energy of node v consists of two parts: its initial energy $w_v(0)$ and the harvested energy $c_v \times \delta$. Denote by f'_v and f'_{c_v} the number of time slots supported by $w_v(0)$ and by $c_v \times \delta$, respectively, then $f_v = f'_v + f'_{c_v}$. It holds that $f_v \times \varepsilon \leq w_v(0) + c_v \times \delta$ and $\varepsilon(\sum_{i\geq 1}(I_{v,i} \times \sum_{q\in N(v)} I_{q,i}) + c_v) \leq \sum_{q\in N(v)} w_q(0)$. Moreover, due to the fact that node v and its neighbors would never be activated at the same time slot in the best case, i.e., $\sum_{i\geq 1}(I_{v,i} \times \sum_{q\in N(v)} I_{q,i}) = 0$, we have $f_v \leq \frac{\varepsilon w_v(0) + \delta \sum_{q\in N(v)} w_q(0)}{\varepsilon^2}$ for node v. Since the number of time slots should be a positive integer, the upper bound of f_v is $\lfloor \frac{\varepsilon w_v(0) + \delta \sum_{q\in N(v)} w_q(0)}{\varepsilon^2} \rfloor$. ■

Step II: We construct a virtual network $G' = (V', E')$ from the original network $G = (V, E)$.

First, for each node $v \in G$, we can create f_v VNs following the result of step I, defined as $C_v = \{v_1, v_2, \ldots, v_{f_v}\}$ in G'. These f_v VNs are completely connected with each other, that is, nodes $v_1, v_2, \ldots, v_{f_v} \in V'$ and edges $(v_i, v_j) \in E'$ for all $1 \leq i < j \leq f_v$. In order to distinguish the ancestor and its VNs, we use function $g(\cdot)$ to express their relationships, i.e., $g(v_i) = v(1 \leq i \leq f_v)$.

Second, for each edge $(v, u) \in E$, we connect all VNs in C_v and C_u in G', meaning $(v_i, u_j) \in E'$ for any $v_i \in C_v$ and any $u_j \in C_u$. As a result, an EH-WBAN can be transformed to a virtual network where the number of VNs and connectivity can represent the energy level and neighbor relationship of their ancestors. Fig. 3 depicts the complete procedure, where the number of VNs of nodes v, u, w are $f_v = 1$, $f_u = 2$, and $f_w = 3$, respectively, in the original network G. According to the abovementioned, corresponding 6 VNs and 15 edges are created in the virtual network G' where the dash lines denote the edges in the same VG while the solid lines represent the edges among different VGs.

Network transformation makes DS population maximization in the original network G no more the objective in the virtual network G'. As a matter of fact, the original problem is transformed to maximizing set of disjoint DSs in G', denoted by S'_{DS}. We start the analysis with the following definition.

Definition 2 (Maximum Set of Disjoint DSs): Let $S'_{DS} = \{DS'_1, DS'_2, \ldots, DS'_l\}$ denote a set of DSs of G', and S'_{DS} is called the maximum set of disjoint DSs of G' if S'_{DS} satisfies the following conditions: (1) DS'_i is a DS of G' for all $1 \leq i \leq l$; (2) $DS'_i \cap DS'_j = \emptyset$ for all $1 \leq i \neq j \leq l$; (3) for $\forall u, v \in DS'_i$ where $1 \leq i \leq l$, their ancestors are different, i.e., $g(u) \neq g(v)$ if $u \neq v$; (4) $l \geq |\hat{S}_{DS}|$ for any set $\hat{S}_{DS}$ that satisfies conditions (1), (2) and (3).

From Definition 2, we can have the following result.

Lemma 2: Let nodes set S be a DS' of G', the set of all their ancestors $\{g(v)|v \in S \bigwedge g(v) \in G\}$ is a DS of G.

Proof: Let G_g define the graph deduced by $\{g(v)|v \in S \bigwedge g(v) \in G\}$. If S is a DS' of G', then for each node $u \in (G' - S)$, there is at least one adjacent node $w \in S$. Recall the rule of constructing a virtual network, if u and w are connected in G', then $g(u) \in G$ and $g(w) \in G_g$ are also connected. There is thus at least one neighbor node $g(w) \in G_g$ for each $g(u) \in (G - G_g)$. Therefore, all nodes in the set of G_g consist a DS of G, and the lemma follows from here. ■

Theorem 2: Let $S' = \{DS'_1, DS'_2, \ldots, DS'_l\}$ denote a maximum set of disjoint DSs of G', $DS_i = \{g(v)|v \in DS'_i \bigwedge g(v) \in G\}$, for all $1 \leq i \leq l$. Then, $S = \{DS_1, DS_2, \ldots, DS_l\}$ is a solution to the sleep scheduling problem 1 defined in Section II.

Proof: Assume that $S = \{DS_1, DS_2, \ldots, DS_l\}$ is not a solution to problem 1. Let $\hat{S} = \{\hat{D}S_1, \hat{D}S_2, \ldots, \hat{D}S_m\}$ denote the optimal solution to our problem, where $m > l$.

The theorem can be proved by the following method which is executed by DSs from $\hat{D}S_1$ to $\hat{D}S_m$ in sequence. Let $\hat{S}' = \{\hat{D}S'_1, \hat{D}S'_2, \ldots, \hat{D}S'_m\}$ and $\hat{D}S'_k = \emptyset$ initially where $1 \leq k \leq m$. First, for each node v in $\hat{D}S_k$, we put v_i in $\hat{D}S'_k$ and update $C_v = C_v - v_i$, where the index of v_i is the minimum in C_v. Second, we repeat these operations for each DS in $\hat{S}$ in ascending order. As a consequence, the following properties hold for $\hat{S}'$: 1) For each $\hat{D}S_k \in \hat{S}$, there is a corresponding $\hat{D}S'_k \in \hat{S}'$ for all $1 \leq k \leq m$, and $\hat{D}S_k$ contains the ancestors of all nodes in $\hat{D}S'_k$. 2) According to lemma 2, each $\hat{D}S'_k \in \hat{S}'$ is a DS of G'. 3) The first step in the proof guarantees that the DSs in $\hat{S}'$ are disjoint mutually. $\hat{S}'$ is thus a set of disjoint DSs in G' and $|\hat{S}'| = m > l = |S'|$, which contradicts with the definition in the theorem that S' is the maximum set of disjoint DSs in G'. Therefore, S_g is a solution of the sleep scheduling problem. ■

Step III: We next discuss how to convert all the discovering disjoint DSs in G' to the original network G. How to find these DSs in G' will be introduced shortly. The converting can be completed in sequence:

- It is necessary to check whether there exists more than one VN from the same VG, which can be verified by checking if there is a $u \in DS'_i$ satisfying that $g(v) = g(u)$ for any $v \in DS'_i$. If so, only one VN is retained while the others are removed from this DS. The operations are repeated for all $DS'_i \in S'_{DS}$ where $1 \leq i \leq l$.
- For each updated DS'_i of G', we look for $DS_i = \{g(v)|\forall v \in DS'_i\}$ that can be proven to be a DS in G following from Lemma 2.
- Repeating the above steps for every $DS'_i \in S'_{DS}$ yields a solution of the DSs set S_{DS} to our problem in G.

Algorithm 1: MinimumDS.

Input: $G(V, E)$ consisting of white nodes
Output: DS consisting of black nodes
$DS = \emptyset$, $k = 1$
while there exists a white node in V **do**
  for all white nodes $v \in V$ **do**
    compute its domination capability D_v^c
    if v satisfies any one of the following conditions:
    (i) v has a strict larger D_v^c than all its white neighbors
    (ii) there exist white neighbors that have the same D^c as that of v, but v has the minimum index
    (iii) none of v's neighbors is white, i.e., $D_v^c = 0$
    then
      $DS = DS \cup v$
      change color of v to black
    end if
  end for
  for all white nodes $u \in (V - DS)$ **do**
    compute its neighbors $\mathbb{N}_{DS}(u)$ in DS
    if $|\mathbb{N}_{DS}(u)| \geq 1$ **then**
      change color of u to grey
    end if
  end for
  $k = k + 1$
end while

Algorithm 2: DisjointDSs.

Input: $G(V', E')$
Output: S'_{DS}
$r = 1$, $S'_{DS} = \emptyset$
repeat
DS'_r =MinimumDS$(G(V', E'))$
for all $w \in DS'_r$ **do**
  $V' = V' - w$
end for
$S'_{DS} = S'_{DS} \cup DS'_r$
$r = r + 1$
until there does not exist a DS in V'

The analysis above proves the feasibility of the transformation from the original network to a virtual one, the key left is to construct a minimum DS, which will be presneted in the following subsection.

B. Constructing the Minimum DS

For a given network, reducing DS size can benefit to increasing the number of DSs, so we should solve the DS size minimization problem in order to maximize the number of DSs. This problem, however, has been proven to be NP-hard in [9]. Therefore, we present an approximation algorithm to find the minimum DS in this subsection.

The algorithm, namely MinimumDS, leverages one-hop neighbor information and a coloring method to find the minimum DS. Initially, let all sensor nodes are white. Then, if one node becomes a dominator, it will be colored black. It will be grey if it becomes a dominatee. Before the formal algorithm description, we introduce a definition of *domination capability* for dominator election.

Definition 3 (Domination Capability): The domination capability D^c of a node is defined as the number of its white neighbors in one hop. D^c of node v is denoted by $D_v^c = |\{u | (u \in N(v)) \cap color_u = white\}|$.

We now start describing MinimumDS shown in Algorithm 1 where $\mathbb{N}_{DS}(u)$ denotes the set of neighbors of node u in set DS and $|\mathbb{N}_{DS}(u)|$ defines its cardinality. Specifically, in each round of the algorithm, each white node first computes its domination capability. Second, the nodes that have the largest domination capability among one-hop neighbors will be elected as dominators and added to DS. If there exist several nodes with the same domination capability, the one with the minimum index will be preferentially chosen. Once a node becomes isolate, i.e., $D_v^c = 0$, it has to be a dominator. All dominators change their colors from white to black. Then, the remaining white nodes check whether they have at least one neighbor in the current DS. If so, they will become dominatees and change to grey. Otherwise, their colors stay white. These operations will be continued until there is no white node in the network. At last, all sensor nodes become black or grey, and the black ones constitute a minimum DS with the upper bound of approximation ratio $1 + \ln \Delta$, which is proven below.

Theorem 3: The Algorithm 1 yields a DS with $(1 + \ln \Delta)opt$ size at most, where Δ is the maximum degree of graph G and *opt* is the size of optimal solution.

Proof: Let S denote the DS set of our solution, and its initial state is $S = \emptyset$. We iteratively choose the optimal node with the maximum degree in one-hop neighbors into set S. The iteration should not terminate until the number of the remaining white nodes is less than the number of nodes in *opt*. At last, all the remaining nodes are added to S. In the worst case, there is only one node becoming a dominator in each iteration. Suppose that there are still U_i white nodes after the i-th iteration, we have

$$U_{i-1} - U_i \geq \frac{U_{i-1}}{opt}, \qquad i = 1, 2, 3, \ldots, \tag{2}$$

where $U_0 = N$. Following Eq.(2), we can derive that

$$U_i \leq U_{i-1}(1 - \frac{1}{opt}) \leq \cdots \leq U_0(1 - \frac{1}{opt})^i.$$

As the iteration will stop when $U_i \geq opt$ while $U_{i+1} < opt$, we have

$$U_0(1 - \frac{1}{opt})^i \geq U_i \geq opt.$$

According to the Taylor Series for $e^{-\frac{1}{opt}}$, it holds that

$$i \leq opt \cdot \ln\Delta.$$

Recall that we pick one node in each iteration, S contains $opt \cdot \ln\Delta$ nodes before the $(i+1)$-th iteration, meanwhile the number of the remaining nodes after the $(i+1)$-th iteration is less than

opt. The number of nodes in DS thus satisfies that

$$|S| \leq (1 + \ln \Delta) opt.$$

Consequently, the upper bound of approximation ratio of Algorithm 1 is $1 + \ln \Delta$. ■

Given the virtual network $G(V', E')$, we can discover all the disjoint DSs based on MinimumDS via pruning all used sensor nodes. This algorithm will continue until there does not exist any DS in G' as described in Algorithm 2.

C. Scheduling the DSs

After obtaining all DSs, we start studying how to appropriately schedule them so that the network lifetime can be extended to the most extent. In this subsection, we present two common scheduling mechanisms: Round-Robin Scheduling and Heuristic Scheduling.

1) Round-Robin Scheduling: As the final DSs set S_{DS} is converted from the disjoint DSs set S'_{DS} where one DS could only work for one time slot, the Round-Robin scheduling mechanism is intuitively regarded as a good method. And this scheduling method is simple and is of low complexity, which is greatly suitable for low-power EH-WBANs. In this mechanism, each DS in S_{DS} takes its turn to work in a circular order until all DSs could not work. The network lifetime is thus equal to the number of rounds which is bounded by the number of disjoint DSs in S'_{DS}.

2) Heuristic Scheduling: From previous experience, a heuristic scheduling mechanism could further extend the network lifetime if we can schedule an optimal DS to work for every time slot. In this approach, we first evaluate the minimum node energy of each DS in current time slot t, i.e., we compute $\min w_v(t)$ for all $v \in DS_i$ where $w_v(t)$ denotes the energy of node v at time slot t. Second, the DS with the most minimum node energy is chosen to work, i.e., $\max(\min w_v(t))$ for $DS_i \in S_{DS}$. At the end of the time slot, each node updates its energy. The process repeats slot by slot until the most minimum node energy in all DSs is smaller than a threshold ϵ, i.e., $\max(\min w_v(t)) < \epsilon$, for all $v \in DS_i$ and $1 \leq i \leq l$. That is, the network could not work any more. This mechanism may perform better in terms of prolonging network lifetime at the cost of higher computational complexity.

D. Algorithm Analysis

Here, we analyze the overall computational complexity of the centralized algorithm. The complexity is $O(\Omega^2|E| + N^3)$, and the proof is stated as follows. First, each node needs to compute its number of VNs, i.e., $\{f_v | 1 \leq v \leq N\}$, with the computational complexity $O(N)$. Second, the original network $G(V, E)$ can be transformed to a virtual network $G(V', E')$ within $O(\Omega N + \Omega^2|E|)$ operations, where $\Omega = max(f_v | 1 \leq v \leq N)$. Then, constructing a minimum size DS via Algorithm 1 needs $O(N^2)$, thus discovering all the disjoint DSs set S'_{DS} in Algorithm 2 needs not larger than $O(N^3)$. At last, in order to convert S'_{DS} to a feasible solution S_{DS}, it costs $O(\Phi)$ where Φ is the minimum node degree in the virtual network G', i.e., $\Phi = min(f_v + \sum_{q \in N(v)} f_q)$ for $1 \leq v \leq N$. Note that the number of disjoint of DSs in G' is smaller than $\Phi + 1$ [7]. Therefore, the overall computational complexity is equal to $O(N) + O(\Omega N + \Omega^2|E|) + O(N^3) + O(\Phi) = O(\Omega^2|E| + N^3)$.

Algorithm 3: EEU Algorithm.

I. Estimating phase
Input: $color_v$, $w_v(t)$
Output: Q_v
$D_v^c = 0$
if $color_v$=white **then**
  broadcast "Hello" message
end if
if v receives "Hello" message **then**
  $D_v^c = D_v^c + 1$
end if
compute $Q_v = (D_v^c)^\alpha \times w_v(t)^{1-\alpha}$

II. Exchanging phase
Input: $color_v$, Q_v
Output: max_v, $equal_v$
$max_v = 0$, $equal_v = 0$
if $color_v$=white **then**
  v broadcasts its Q_v
end if
if v receives Q_u from neighbor u **then**
  if $Q_u > Q_v$ **then**
    $max_v = max_v + 1$
  end if
  if $Q_u = Q_v$ **then**
    $equal_v = equal_v + 1$
  end if
end if

III. Updating phase
Input: max_v, $equal_v$, $color_v$, $w_v(t)$, ε, δ
if i) $max_v = 0$ and $equal_v = 0$ or
  ii) $max_v = 0$, $equal_v \neq 0$ and $v < u$ **then**
  v broadcasts a "Dominator" message
  $color_v = black$
  $w_v(t+1) = w_v(t) - \varepsilon$
end if
if v receives a "Dominator" message **then**
  $color_v = grey$
  $w_v(t+1) = w_v(t) + \delta$
end if

IV. Distributed Solutions

An EH-WBAN of light-weight sensors prefers lower-complexity algorithms, so the centralized algorithm that needs a prior global information may be not the best for EH-WBANs. This section presents two distributed algorithms that can work without global knowledge to improve the network scalability.

Using the domination capability and the coloring method, the distributed algorithm selects the sensor nodes with the highest local weight into DS in each iteration. Specifically, each iteration of our algorithm, namely **EEU**, consists of three phases: Estimating phase, Exchanging phase and Updating phase. In the estimating phase, each node computes its local weight Q_v in current time slot. Then, all sensor nodes exchange their information in the exchanging phase. Finally, the nodes with the maximum Q_v are added to DS in the updating phase. In order to select the dominators, each node needs to maintain 6 variables, i.e., $color_v, D_v^c, w_v(t), Q_v, max_v$ and $equal_v$. $color_v$ that represents the current state of node v is initialized to white, and it will be changed to black or grey if node v becomes a dominator or dominatee. D_v^c and $w_v(t)$ denote the domination capability and residual energy of node v in time slot t respectively. Q_v indicates the local weight of node v in current time slot. max_v denotes the number of neighbor nodes that have bigger local weight than Q_v. $equal_v$ is the number of neighbor nodes with the same local weight as Q_v. We next detail the distributed algorithm shown in Algorithm 3 for an arbitrary node $v \in V$.

A. Algorithm Description

1) Estimating phase: The aim of this phase is to evaluate the domination capability and local weight of node v in current time slot. As shown in Algorithm 3, the node v broadcasts a "Hello" message if its color is white. Once v receives a "Hello" message from neighbors, its domination capability D_v^c is increased by 1. Otherwise, it will remain unchanged. Then, v calculates its local weight according to $(D_v^c)^\alpha \times w_v(t)^{1-\alpha}$, where $\alpha \in (0, 1]$ defines the favorable level for the domination capability or residual energy.

2) Exchanging phase: After the estimating phase, node v tries to exchange local weight Q_v with its neighbors. In the beginning, if $color_v$ is white, v broadcasts its Q_v. When v receives a Q_u from neighbor u, its max_v increases by 1 if Q_u is larger than its Q_v. Correspondingly, the $equal_v$ is increased by 1 as long as Q_u is equal to Q_v.

3) Updating phase: In this phase, if node v has the largest local weight Q_v, it will be a dominator. It then broadcast a "Dominator" message while changing its color to black and updating its residual energy for next slot to $w_v(t) - \varepsilon$. If none of v's neighbors has a greater local weight than v and there exists neighbor u has the same local weight with v and v has the minimum index, i.e., $v < u$, v will also become a dominator. Once v receives "Dominator" message from one of its neighbors, it becomes a dominatee with its color changed to grey and its residual energy updated to $w_v(t+1) = w_v(t) + \delta$ for next slot. Otherwise, node v maintains its current color.

After executing the three phases, if node v still be white, it will perform Algorithm 3 repeatedly until it becomes black or grey. As a result, this distributed algorithm yields a DS for time slot t, and it will be successively executed until there does not exist any DS in the network.

B. Algorithm Analysis

The complexity of EEU algorithm is investigated as follows. In the beginning, each node $v \in V$ needs to exchange messages with its neighbors, and then computes its local weight Q_v in the estimating phase. The communication and computation cost are $O(\Delta)$, where Δ is the maximum node degree. Then, in the exchanging phase, each node v broadcasts its local weight Q_v and receives local weights from its neighbors, and evaluates the number max_v and $equal_v$. The communication and computation cost are also $O(\Delta)$. In the third phase, each node updates its color and residual energy based on max_v and $equal_v$, and only the dominators need to broadcast message. Therefore, the computation complexity is $O(1)$, while the communication cost is at most $O(\Delta)$. In summary, the communication and computation cost of Algorithm 3 are both $O(\Delta)$.

Algorithm 4: Improved EEU Algorithm.

Input: $color_v, Q_v, \varepsilon, \delta$
compute $T_v = F(Q_v)$
if v has not received any message before T_v **then**
  v broadcasts a "Dominator" message
  $color_v = black$
  $w_v(t+1) = w_v(t) - \varepsilon$
end if
if v has received message from neighbor u before T_v **then**
  $color_v = grey$
  $w_v(t+1) = w_v(t) + \delta$
end if

C. Improved Distributed Algorithm

In the exchanging phase of Algorithm 3, all sensor nodes have to broadcast their local weights and receive local weights from their neighbors in order to compete for the dominators, leading to heavy communication cost. To overcome this shortcoming, we propose an **improved EEU** algorithm where a waiting time is defined for each sensor node to reduce both computation cost and communication cost.

In the improved EEU algorithm, we assume that all sensor nodes are synchronized. Let T_v denote the waiting time of node v, which is set to $F(Q_v)$ where $F(\cdot)$ a strictly monotone decreasing function. For two nodes v and u, if their local weights satisfy that $Q_v > Q_u$, then their waiting time is set as $T_v < T_u$, meaning that node v broadcasts message earlier than u. Similarly to EEU, at the end of the estimating phase, each node v obtains its local weight Q_v. Then, it computes its waiting time T_v based on Q_v. If node v has not received any message before its waiting time T_v expires, that is, none of its neighbors has larger local weight than Q_v, it broadcasts a "Dominator" message, changes its color to black and reduces its residual energy by ε. If node v has received message from any neighbor u before T_v, it will be a "Dominatee" and will change color to grey while updating its residual energy to $w_v(t) + \delta$ for next slot. The detailed algorithm for an arbitrary node v is summarized in Algorithm 4.

Although the communication and computation complexities of Algorithm 4 are also both $O(\Delta)$, they are actually reduced to two thirds of Algorithm 3 due to the fact that the improved EEU algorithm does not implement the first phase of EEU so that the corresponding cost is saved.

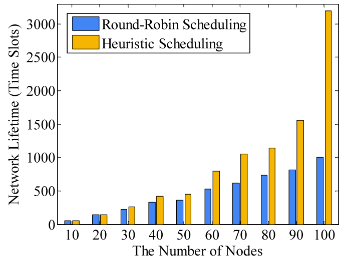

Fig. 4. The network lifetime of our centralized algorithm.

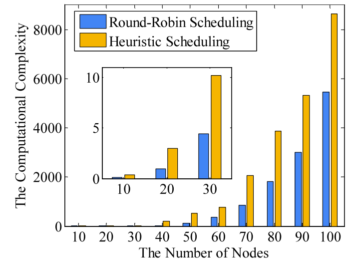

Fig. 5. The computational complexity of our centralized algorithm.

V. Performance Evaluation

In this section, we conduct simulations to evaluate the algorithm performance. Following IEEE 802.15.6 standard [6] that a WBAN can support up to 256 sensor nodes, we vary the number of nodes from 10 to 100. Initially, each node has 1 unit energy by default, and it will consume 0.1 unit energy if it works in a DS in one time slot. In consideration of the current energy harvesting technique, the energy harvesting rate is much smaller than energy consumption rate, especially for human-based energy harvesting [10] [11], we set the charging rate to 0.001 unit energy per slot.

To comprehensively evaluate the performance, we assess the proposed algorithms with the following metrics:

- *Network lifetime:* For each time slot, one DS will be constructed to work to ensure the real-time requirement of WBAN, and the nodes not in the DS can switch to sleep state to conserve energy. Based on the Definition 1, the network lifetime can be measured by the time slot that there does not exist any DS in the network.
- *Execution time:* Since the limited capability of sensor nodes in WBANs, the execution time spent constructing DSs is investigated to justify the efficiency of our proposed algorithms.
- *Cardinality of DS:* The DS size determines directly the energy consumption of the whole network in each time slot, which makes great impact on the network lifetime.

In what follows, we first investigate the impact of round-robin scheduling and heuristic scheduling mechanisms on our centralized algorithm, and then the impact of α on EEU algorithm. We conduct performance comparison among the proposed schemes and centralized STG algorithm [12] that schedules nodes to form virtual backbone. Note that all results are calculated from 100 independent experiments.

A. Algorithm Investigation

1) In our centralized algorithm, the DSs scheduling mechanism can also play an import role on the network lifetime besides the number of DSs and the size of a DS. Thus, we need to adopt an appropriate scheduling mechanism to extend the network lifetime. In this subsection, we perform simulations to evaluate two scheduling mechanisms: Round-Robin Scheduling and Heuristic Scheduling.

Fig. 4 depicts the network lifetime under two scheduling mechanisms, from which we can draw that our centralized algorithm can achieve longer network lifetime under heuristic scheduling mechanism than round-robin scheduling mechanism. The main reason is that the heuristic scheduling mechanism chooses the optimal DS whose minimum node residual energy is maximum to work in each time slot. In contrast, the round-robin mechanism schedules does not differentiate DSs.

We proceed to evaluate the computational complexity of two scheduling mechanisms as shown in Fig. 5. From the results, we can find that the computational complexity of the heuristic scheduling is much higher than the round-robin scheduling. Considering the limited computational capability of sensor nodes in WBANs, the round-robin scheduling mechanism is more appropriate choice for its simplicity and low complexity, especially for the small-scale networks.

2) In the EEU algorithm, α indicates the preference of the algorithm for the node domination capability or residual energy during the dominator election. Thus, we need to adopt an appropriate value α for the network lifetime maximization.

In the simulations, we consider three scenarios with the network size varied from 20 to 60 with step length of 20. In each scenario, there are three kinds of networks with the same size but different average node degrees: (a) smaller than half of the number of nodes, (b) equal to half of the number of nodes, (c) greater than half of the number of nodes. Fig. 6 shows the results of the network lifetime under different value of α in three scenarios, respectively. Note that in order to guarantee the network reliability, the results depicted in Fig. 6 when $\alpha = 0$, are the values when $\alpha = 0.001$.

From these figures, we can observe that the network lifetime is maximum as $\alpha \in [0.5, 0.6]$ when the network size is 20. When the network size increases to 40 and 60, the network lifetime achieves the maximum value when $\alpha \in [0.7, 0.8]$ as shown in Fig. 6(b) and (c), respectively. Moreover, a quantitative comparison can be made from Fig. 6 that the maximum network lifetime is average 27%, 23% and 18% longer than that when $\alpha = 1$ (i.e., the domination capability is the only criterion to choose the final dominator). The results demonstrate that the domination capability plays an important role in constructing DS in EEU algorithm, and it is more important than residual energy in terms of prolonging the network lifetime. Motivated by the observations, we set $\alpha = 0.7$ for EEU in the following simulations.

B. Performance Comparison

1) Network lifetime: In this section, we compare our algorithms with the centralized algorithm STG [12] in terms

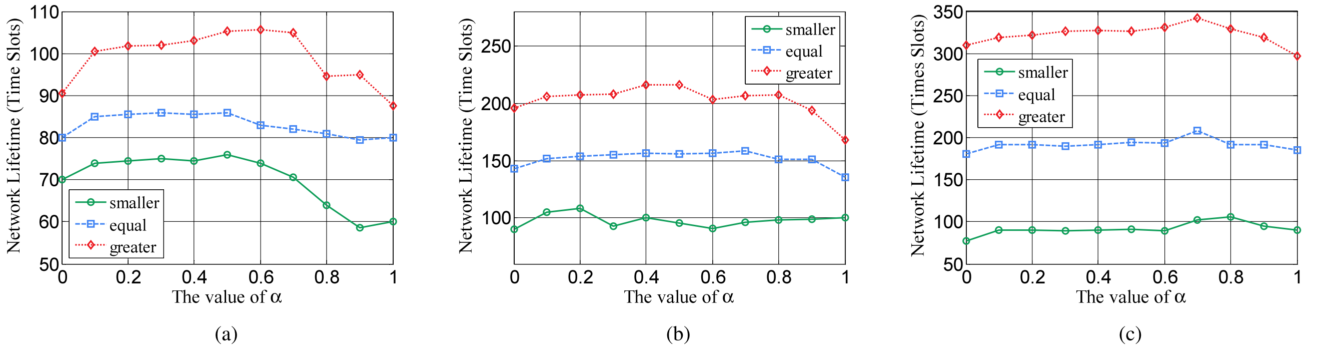

Fig. 6. The impact of α on the network lifetime under different network size: (a) 20 nodes, (b) 40 nodes, (c) 60 nodes. ('smaller' in the legend means the average node degree is smaller than half of the number of nodes; 'equal' means the former is equal to the latter; 'greater' means the former exceeds the latter). (a) Size = 20. (b) Size = 40. (c) Size = 60.

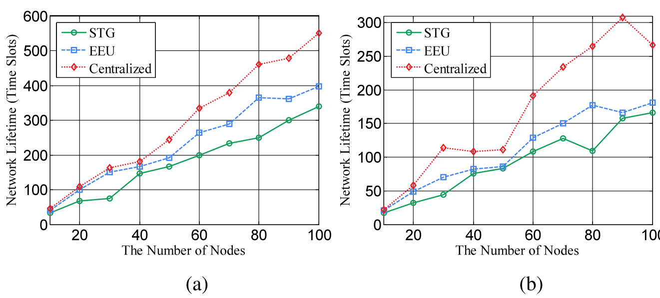

Fig. 7. The network lifetime comparison of our centralized algorithm and EEU vs. STG. (a) Uniform distribution. (b) Random distribution.

of the network lifetime. The network size varies from 10 to 100, and two types of node energy distribution are considered: (a) uniform distribution: each node has 1 unit initial energy, (b) random distribution: each node is assigned a random initial energy from [0,1] unit.

Fig. 7 illustrates that our centralized algorithm and distributed EEU algorithm perform better than STG in prolonging the network lifetime in that the energy level is the only one parameter considered for backbone construction in STG. In our algorithms, the domination capability is also taken into consideration, which has more impact on prolonging network lifetime than the energy level as verified in Fig. 6. Specifically, the network lifetime of our centralized algorithm (EEU) is 84% (46%) longer than that achieved by STG on average in Fig. 7(a) with uniform energy distribution. The gain increases to 95% (62%) in the scenario with random energy distribution, as shown in Fig. 7(b). These results demonstrate that our proposed sleep scheduling schemes are highly energy-efficient.

As the problem addressed by STG [12] is different from ours, we next focus on performance evaluation of our centralized and distributed algorithms in terms of the three metrics in three cases. (a) Full-Energy-Harvest (FEH): All nodes have the capability to harvest energy when they do not work in DSs. (b) Part-Energy-Harvest (PEH): Only partial nodes can recharge when they are dominatees. (c) No-Energy-Harvest (NEH): All nodes cannot harvest energy. They have the same topology and the initial energy of each node is distributed uniformly. Note that we set that 50% of the nodes are rechargeable under PEH in the simulation. The results are depicted in Fig. 8 where we can make the following observations:

- The centralized algorithm achieves the longest network lifetime while EEU performs better than Improved EEU. The main reason is that the centralized algorithm maintains global information of the whole network, enabling DS size minimization, while only the local information of one-hop neighbors can be used in the distribution ones. Moreover, in order to reduce the computational cost, Improved EEU introduces waiting time T influencing dominator or dominatee decision in one round, which increases the cardinality of DS and leads to much energy consumption. However, the complexity of the centralized algorithm is the highest, which will be assessed shortly.
- The network lifetime in case (b) is longer than case (c), and case (a) can achieve the longest network lifetime, which further demonstrate that energy harvesting technique is an effective and promising approach from the perspective of prolonging the network lifetime.

2) Execution time: In order to justify the algorithm efficiency, we further evaluate their computation cost. From Fig. 9, we can find that the centralized algorithm spends more time than EEU. Specifically, the execution time of the former follows the high-order polynomial growth with network scale while that of EEU stays constant, matching with analytical results. The similar conclusion can be drawn from Fig. 10 that Improved EEU can dramatically reduce the execution time compared to EEU. This can be interpreted as follows: In EEU, each node needs to exchange and compare its local weight with its all neighbors in the exchanging and updating phases. In contrast, Improved EEU overcomes this shortcoming effectively by introducing waiting time for each node.

3) Cardinality of DS: We also record the minimum DS cardinality of the two distributed algorithms. As shown in Fig. 11, EEU builds smaller DS than Improved EEU that needs less knowledge, and is thus more energy-efficient, which is in accordance with the results shown in Fig. 8.

In summary, the centralized algorithm can achieve longer network lifetime compared to the distributed algorithms. However, it is not suitable for EH-WBANs with large number of sensor

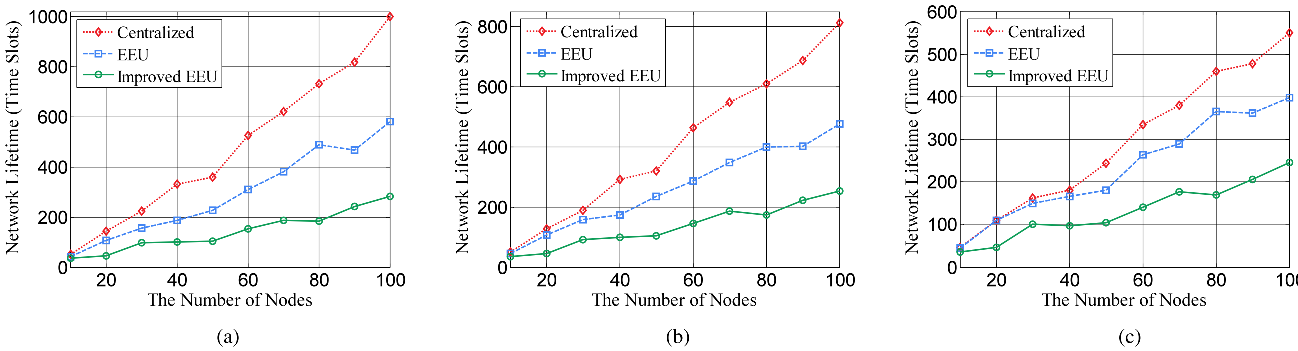

Fig. 8. The network lifetime comparison of our centralized algorithm, distributed EEU algorithm and Improved EEU algorithm. (a) Full-Energy-Harvest (FEH). (b) Part-Energy-Harvest (PEH). (c) No-Energy-Harvest (NEH).

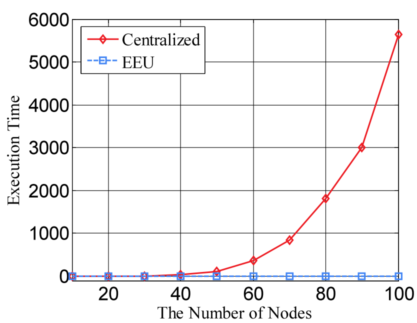

Fig. 9. Execution time: Centralized vs. EEU.

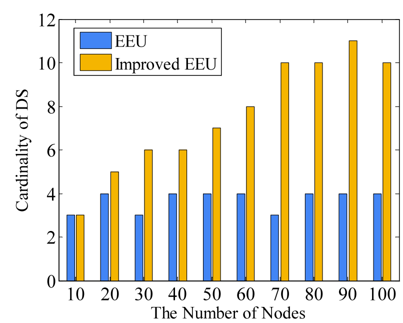

Fig. 11. The cardinality of DS.

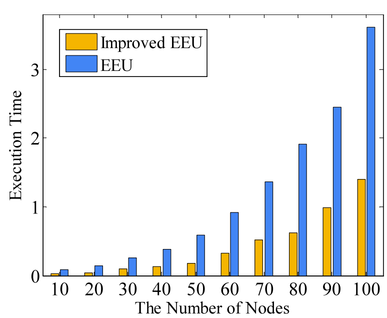

Fig. 10. Execution time: EEU vs. Improved EEU.

nodes due to the sharply increasing computational complexity with network scale. In contrast, EEU and Improved EEU are more computation-efficient and do not need global knowledge of the network. Therefore, the three algorithms are suitable for different application scenarios of EH-WBANs and users could pick one according to their situations.

VI. Related Work

The sleep scheduling problem has not yet been studied in the context of energy-harvesting scenarios for WBANs. Although a number of algorithms have been proposed to address the sleep scheduling problem in traditional Wireless Sensor Networks (WSNs), they do not involve two dimensions simultaneously, i.e., energy-saving and energy-harvesting techniques. To the best of our knowledge, this is the first effort so far to design the sleep scheduling algorithms for EH-WBANs.

Due to efficiency of duty cycling technique on energy conservation, duty cycling MAC protocols for WBANs have been studied in [13], [14], where sensor nodes adjusted their duty cycle periods according to the time-division multiple access strategy or carrier sense multiple access with collision avoidance strategy. The authors [12] proposed Virtual Backbone Scheduling (VBS) that was a sleep scheduling technique by forming multiple overlapped backbones to prolong the network lifetime for redundant WSNs. A self-adaptive sleep/wake-up scheduling approach was proposed based on game theory and the reinforcement learning technique, where each node could autonomously decide its own sleep, listen or transmission according to its current situation and an approximation of its neighbors' situations in each time slot by a decentralized manner [15]. Recently, an energy-efficient sleep scheduling problem in WBANs was investigated from the perspective of minimum dominating set in our previous work [16], where a global approximation algorithm and a local approximation algorithm were proposed to construct m-fold dominating set in order to schedule nodes awake/asleep status while guaranteeing network reliability. None of these works, however, takes into consideration energy-harvesting case.

Energy-harvesting technique is as an efficient approach of energy provision. Armed with energy-harvesting functionality through solar panel, wind generator and RF energy harvester, a sensor node can harvest energy from its ambient environment.

In [17] the authors proposed a two-stage sleep scheduling algorithm for solar-powered WSNs, where the precedence operator-based group formation algorithm was first designed to ensure the desired area coverage. A Q learning-based active node selection algorithm was provided for the nodes to select their working modes in order to adapt to the dynamic environment. For the rechargeable WSNs, two novel collaborative location-based sleep scheduling schemes were presented in [18], where each sensor node could dynamically determine the awake or asleep status by integrating mobile cloud computing with WSNs. Tuo *et al* [8] conduct backbone for general energy-harvesting networks where the scheduling problem is formulated as finding disjoint connected dominating set problem, while we focus on designing the minimum DS discovery algorithm. Our work is compatible with IEEE 802.15.6 where two-hop communication at most is allowed, which is not held in this work for its multiple-hop routes. In order to guarantee an energy-neutral condition to avoid energy harvesting nodes from early energy exhaustion, a sleep scheduling scheme modeling three-state Markov chain was proposed to handle the coverage and connectivity during less-energy-harvesting intervals in [19]. These algorithms for WSNs, however, cannot be directly applied to duty-cycling EH-WBANs where the computational and communication capabilities of sensor nodes are far constrained.

In summary, no existing work has been done on the sleep scheduling problem with the consideration of two dimensions of energy-saving and energy-harvesting in practical EH-WBANs. In contrast, this paper combines them to studies sleep scheduling problem systematically in EH-WBANs from the perspective of theoretical framework and algorithm design.

VII. Conclusion

In this paper, we have defined and investigated the sleep scheduling problem arising in Energy Harvesting WBANs (EH-WBANs) through constructing Dominating Set (DS). We have shown the NP-hardness of the sleep scheduling problem, and proposed three approximation algorithms to address this problem. More specifically, the designed centralized algorithm could use global network information to find the maximum number of DSs and construct the minimum DS. To reduce computational complexity, two distributed algorithms namely EEU and Improved EEU, have further been developed which only need local information. We have also conducted theoretical analysis and extensive simulations. The results confirm that the proposed algorithms could considerably prolong the network lifetime and ensure the network connectivity by constructing DS in EH-WBANs.

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