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EnergIoT: A solution to improve network lifetime of IoT devices

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ABSTRACT

Internet of Things (IoT) is a novel paradigm attracting significant attention in the modern wireless telecommunications field. However, in some scenarios, the performance of IoT network is limited by energy-constrained devices. In order to improve the energy efficiency of such IoT devices, researchers have proposed several approaches based on duty cycle operation (switching devices between sleeping and active mode). However, current solutions adopting duty cycle (i.e., the fraction of time in which a node is active) have three issues: (i) they assign the same duty cycle ratio to all the nodes without balancing energy consumption; or (ii) they distribute different duty cycle ratios without considering the energy consumption during *network construction* phase; or (iii) their network structure models are based on concentric corona, instead of clustering structure.

In this paper, we propose EnergIoT, a hierarchical clustering approach based on duty cycle ratio to maximize network lifetime of battery-powered IoT devices. In particular, we assign different duty cycle ratios to devices according to their distance from the sink, since different duty cycle ratios balance the energy consumption among devices at different layers. Furthermore, we calculate the energy consumption of IoT devices, considering both *network construction* phase and *data processing* phase. We evaluate EnergIoT through extensive simulation analyses on the OMNet++ platform. The result shows that EnergIoT is not only feasible but also efficient. Moreover, EnergIoT improves the network lifetime by 32%, compared to the uniform duty cycle approach, without sacrificing the network performance (i.e., end-to-end delay).

1. Introduction

Internet of Things (IoT) is a novel paradigm that is rapidly gaining ground in the scenario of modern wireless telecommunications. In recent years, IoT is attracting significant attention from both academia and industry [1,2]. IoT can be used in the fields of environmental monitoring [3], health-care [4], and smart cities [5]. Besides, it can be used to leverage sensor devices to gather valuable data [6] and so forth. IoT devices are widely used as effective transmission medium [7]. However, IoT devices considered in the aforementioned work are restricted in terms of battery energy, processing, memory, and transmission range.

Fig. 1 shows a network structure of battery-powered IoT devices, in which, the battery-powered IoT devices connect with the outside world via one or several sinks/gateways. The sink is a base station, which is used to collect and process data in a centralized mode. In this paper, we use "network", "sink" and "nodes" to represent the IoT network, the rendezvous point and battery-powered IoT devices, respectively.

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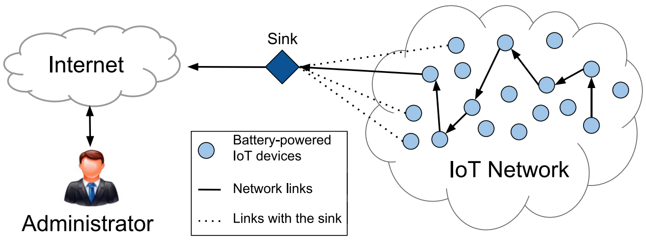


Fig. 1. The structure of a network of battery-powered IoT devices.

In IoT, sensor nodes are restricted by limited batteries and transmission range. Thus, if nodes cannot communicate with sink directly, they leverage other peers as forwarders to route traffic to sink. In such case, the nodes closer to the sink carry heavier traffic loads. As a result, inner layer nodes deplete their energy faster than other peers [8]. Consequently, a massive amount of energy (i.e., remaining energy in the devices far away from the sink) is wasted and the network lifetime ends prematurely. Wadaa et al. in [9] showed that by the time nodes closest to the sink deplete their energy, the farther nodes may still have 93% of their initial energy available. This phenomenon is called *energy hole* problem [10].

In order to cope with *energy hole*, researchers have proposed several approaches based on duty cycle operation. Generally, nodes spend a large portion of power on monitoring surrounding environment instead of communicating with other nodes. This monitoring behavior is called *idle listening* [11]. In order to save energy by idle listening and balance the energy consumption, duty cycle ratio (i.e., periodically switching devices between sleeping mode and active mode) is being widely used in designing protocols for the IoT network of battery limited devices [12–14]. However, three issues exist in the energy conservation approaches applied with duty cycle ratios. First, the approaches assigning the same duty cycle ratio to all the nodes lead to a quick ending of network lifetime. According to the definition of *energy hole*, the inner nodes consumed more energy than the outer nodes and quickly ran out of their energy. Without the cooperation of inner nodes, the network cannot work properly and ends their lifetime quickly. Second, some protocols distribute different duty cycle ratios for different layers' nodes, however, they did not take the energy consumption during *network construction* phase. In other words, network lifetime is composed of *network construction* phase and *data processing* phase. Third, some of them focus on calculating energy consumption based on the concentric corona. However, compared with concentric corona structure, clustering structure is considered an effective approach to address the energy hole problem and prolong network lifetime [15–17]. One energy conservation approach is to prolong the network lifetime by adjusting the duty cycle ratios, unfortunately, it degrades network performance (i.e., increasing end-to-end delay). Therefore, we propose an energy conservative approach, EnergIoT, which could mitigate the *energy hole* problem and extend the network lifetime, without sacrificing network performance.

Contribution.

In this paper, we propose EnergIoT, a hierarchical clustering approach based on different duty cycle ratios, which aims to maximize the lifetime of an IoT network of battery-powered devices. As pointed out above, the network based on clustering structure is efficient in energy conservation in a large scale network for battery-powered nodes. Hence, EnergIoT leverages the clustering structure to manage the nodes and to improve efficiency of such IoT networks. In addition, we propose an approach in order to compute and assign the optimal duty cycle ratio to each node in the network according to the layer which it belongs to. It allows us to balance their energy consumption, especially to balance the nodes in both the innermost layer and the outermost layer. In order to do so, we model duty cycle ratio considering both *network construction* phase and *data processing* phase. Moreover, we achieve the target of energy conservation without sacrificing network performance, compared to uniform duty cycle approaches.

In summary, the advantages of EnergIoT is listed as follows:

- We take the energy consumption of idle listening into consideration not only in *network construction* phase but also in *data processing* phase.
- Leveraging on the hierarchical clustering structure, EnergIoT is able to balance the energy consumption in different layers, and thus it avoids *energy hole* problem with assignation of different duty cycle ratios for nodes in different layers.
- As highlighted by the results of the thorough evaluation we carried out, EnergIoT extends the lifetime of an IoT network of battery-powered devices by 32% more than that of uniform duty cycle approaches without decreasing network performance.

Organization.

The rest of this paper is organized as follows. We survey the state-of-the-art of the energy efficiency in IoT network of battery-powered devices in Section 2. In Section 3, we first discuss the network structure of EnergIoT. Then, we describe the energy model considered in this paper. In Section 4, we give a detailed description of our two objectives and we leverage mathematical method to get optimal values of different duty cycle ratios via our objectives. In Section 5, we report and discuss the result of the simulation. Finally, we draw the conclusions in Section 6.

2. Related work

With the development of Internet technology and Wireless Sensor Networks (WSNs), a new paradigm for communication called Internet of Things is emerging in the era of ubiquity [18]. IoT network is full of smart "network enabled" objects, such as, smartphones, smart vehicles, buildings and other items embedded with electronics, software, sensors, actuators. Such smart objects have capabilities of sensing, acting, communicating, and processing advanced signal and information. IoT sensors play an important role in collecting, sending, and receiving a significant amount of data. Sensing and transmitting data are also key capabilities of WSNs. Therefore, most of the problems regarding the energy consumption in WSNs are inherited by IoT paradigms as well.

In recent years, researchers have proposed numerous approaches aiming at optimizing energy consumption. The authors in [19] are the first to study how to avoid *energy hole* problem in WSNs. They proposed an energy consumption model governed by $E = d^\alpha + c$, where d is the transmission range, α is energy consumption coefficient and c is a positive constant parameter. They proved in theory that uneven energy depletion can be avoided when the width of all the coronas are same. C. Song et al. in [20] assigned different transmission ranges for different nodes to avoid *energy hole* problem. Based on the work [20], the authors in [21] found the optimal transmission path between each node and sink through ant colony algorithm. X. Wu et al. in [10] investigated the theoretical aspects of the non-uniform node distribution strategy. In particular, they regulated the number of nodes in each corona and derive the ratio q between the node densities in the adjacent $i + 1$th and ith coronas by the strategy. However, they did not consider the energy consumption in *network construction* phase and idle listening consumption in *data processing* phase.

The authors in [22,23] proposed their own algorithm to find the most energy-efficient path to the sink for processing and storing data collected from sensors. Although all the aforementioned literature tried to solve the *energy hole* problem, some of them did not take the energy consumption caused by idle listening into consideration (e.g., [24]). In many scenarios, sensor nodes usually spend a considerable proportion of energy for monitoring the environment without communication, hence, the energy consumption of idle listening cannot be ignored. In order to reduce the energy consumption of idle listening and balance energy consumption in different layers, the protocols of WSNs usually adopted duty cycle operation, which means nodes' working pattern alternates between sleeping and active mode. M. Medidi and Y. Zhou in [14] assigned different duty cycle ratios for nodes according to the distances from the sink. However, this model did not consider energy consumption caused in *network construction* phase, and did not rely on the clustering architecture that is efficient in energy conservation in a large scale network. Compared to the existing approaches, EnergIoT strategy proposed in this paper not only considers energy consumption in *network construction* phase and *data processing* phase based on the hierarchical clustering structure, but it also assigns different duty cycle ratios for nodes to balance the energy consumption to cope with energy hole problem.

3. Network model and energy consumption in EnergIoT

In order to present our EnergIoT—a hierarchical clustering approach based on different duty cycle ratios to improve the energy efficiency of a network of IoT devices, we introduce the network structure model for EnergIoT in Section 3.1. Based on the network structure, network lifetime is divided into *network construction* phase and *data processing* phase in EnergIoT (details in Section 3.2). In Section 3.3, we illustrate the energy model for calculating the energy consumption.

3.1. Network structure model

We assume that all the nodes are distributed in an area where the sink is located at the center of the network. All the sensor nodes are distributed within a distance R from the sink. The density of node distribution is ρ and the width of each layer is r that is the maximum transmission radius of sensors. We divide the network into m layers and set the ID of sink layer as 0, the ID of the outermost layer as m and so on. Since the maximum transmission range of a sensor node is r, the network is composed of a set of concentric coronas whose width is r. The data generated by nodes whose distance from the sink is larger than r is transmitted to the sink by multi-hop forwarding.

In EnergIoT, we manage and coordinate the nodes by leveraging hierarchical clustering architecture. Fig. 2 shows the hierarchical clustering architecture. For ease of exposition, we show only a part of a whole network. A cluster consists of a cluster head (CH) and several cluster nodes (CNs). In particular, CNs are located in the same layer, exactly within the transmission range of the CH. CH is responsible for forwarding data gathered by its CNs to its inner layers' CH. Based on this structure, a node could play different roles in different clusters. For example, node a, located at layer 2, acts as (i) a CH to receive data from its CNs located at layer 3, and (ii) a CN to transmit traffic to its CH located in layer 1. Recalling that a CH acts as a forwarder, we assume the ratio of the number of CH to the total CNs as μ. Moreover, each source node generates and sends λ bits of data per unit time.

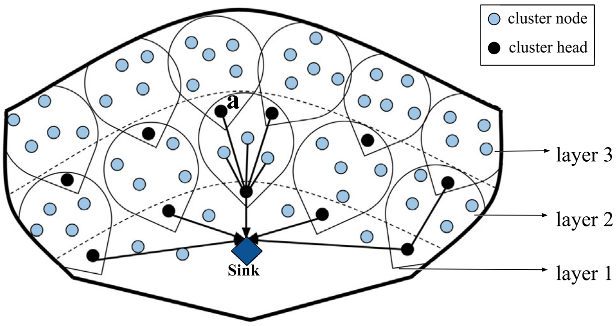


Fig. 2. Hierarchical clustering architecture.

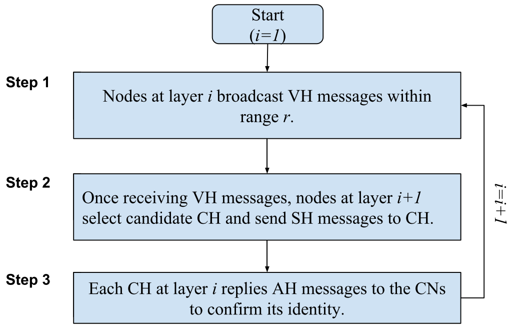


Fig. 3. Procedure of network construction.

3.2. *Network workflow*

Based on the above hierarchical clustering architecture, we give a description of the network workflow. The lifetime of the network consists of several rounds. When the number of dead sensor nodes (run out of energy) is larger than a threshold, the sink node starts the next round to "refresh" the *network construction* phase (see details in Section 3.2.1). Besides, each round includes two phases: *network construction* phase and *data processing* phase.

3.2.1. *Network construction phase*

During the *network construction* phase, EnergIoT uses multiple iterations to discover all the sensor nodes, and forms a hierarchical clustering architecture. The procedure of *network construction* phase is shown in Fig. 3.

In each iteration, nodes at layer i broadcast VH (Vie cluster Head) messages within range r to vie to be CH. A VH message includes the following information: remaining energy of the node and the identifier of the layer where the node is located (Step 1). Once a node located at layer $i+1$ receives VH messages from several CH candidates, it chooses the one which locates closest and remains more energy to be its CH. Then, the node sends a SH (Selecting cluster Head) message to the selected CH candidate (Step 2). The selected CH candidate at layer i replies AH (Ack cluster Head) messages to the nodes who are located at layer $i + 1$ and selects the candidate CH as their CH (Step 3).

Nodes at layer $i+1$ broadcast VH messages to nodes at layer $i+2$ to start a new iteration. Similarly, other CHs are found in different layers. Finally, in EnergIoT, after the *network construction* phase, we have the network where nodes are partitioned into layers according to their distances to the sink.

3.2.2. *Data processing phase*

During the *data processing* phase, each node in the network has two modes: *active* and *sleep*. In active mode, nodes consume energy to sense (i.e., idle listening), receive and transmit data. While in sleep mode, nodes are able to reduce energy consumption by turning off the sensing function. The duty cycle ratio γ, is defined as follows [11]:

$$\gamma = \frac{T_{active}}{T_{active} + T_{sleep}}$$

where T_{active} represents the duration of active mode and T_{sleep} is the duration of sleep mode. Note that, we can only adjust the duty cycle of a node by varying T_{sleep}, since T_{active} is fixed in order to guarantee receiving and transmitting network package [25].

3.3. Energy consumption model

In this section, we discuss the model for the possible energy consumption in EnergIoT. We assume that sensor nodes have the same initial energy, and the power of the sink is unlimited.

First, we list the following types of energy consumption during *data processing* phase:

- E_{gl}: the average energy consumed for idle listening (active mode) in one unit time;
- E_{gr}: the average energy consumed for receiving data in one unit time;
- E_{gs}: the average energy consumed for transmitting data in one unit time.

In particular, E_{gl} is controlled by the duty cycle γ, the equation is listed in Eq. (1).

$$E_{gl} = \gamma e_{idle}. \tag{1}$$

Here, e_{idle} denotes a node's energy consumption for idle listening in per unit time [24]. Moreover, we set the value of e_{idle} to 0.88 mJ/s for our EnergIoT. In order to calculate the energy consumption of sending and receiving packets (E_{gr} and E_{gs}), we list two basic formulas. The consumed energy in receiving l-bit data is shown in Eq. (2) and the consumed energy in sending l-bit data over a distance r is given by Eq. (3). Similar to the work [26], we assume a simple model where the radio dissipates $E_{elec} = 50$ nJ/bit to run the transmitter or receiver circuitry.

$$E_{gr} = lE_{elec}. \tag{2}$$

$$E_{gs} = l(E_{elec} + \varepsilon r^{\alpha}). \tag{3}$$

Second, we consider the following two types of energy consumption in *network construction* phase:

- E_{cl}: the energy consumed for idle listening in one unit time.
- E_{csr}: the energy consumed for receiving and transmitting messages (i.e., VH, SH and AH messages as described in Section 3.2.1) in one unit time.

In the following section, we illustrate concretely how to calculate the energy consumption in different layers and balance energy consumption among different layers.

4. Energy consumption optimization in EnergIoT

In this section, based on the network structure and energy model, we illustrate the main design of EnergIoT. In detail, we describe two objectives in Sections 4.1 and 4.2, respectively. According to the objectives, we take methods to find the optimal value of different duty cycle ratios for each layer in Section 4.3.

4.1. Objective: balancing energy consumption in different layers

In order to accomplish this objective, we need to calculate the different type energy consumption of each layer's nodes in EnergIoT according to the order shown in Section 3.3.

We use E_{gl}^{i} to represent the average idle listening energy consumption of CH in layer i in one unit time during *data processing* phase. The energy consumption for idle listening is also up to the ratio of CH. In EnergIoT, we assign different duty cycles for nodes at different layers. The duty cycle of a node at layer i is γ_i, and hence we have:

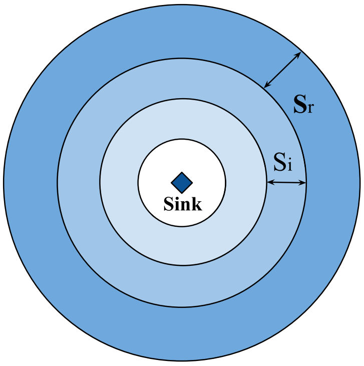
$$E_{gl}^{i} = \mu \gamma_i e_{idle}. \tag{4}$$

We denote E_{gr}^{i} as the average energy consumption of each node for receiving data at layer i in one unit time. In EnergIoT, a node at layer i receives data collected from all outer layers (i.e., from $i+1$th layer to mth layer). As shown in Fig. 4(a), nodes in area S_i receive data generated from the nodes in area S_r. Note that, S_r includes one or more layers. Thus, according to Eq. (2), E_{gr}^{i} can be calculated as Eq. (5).

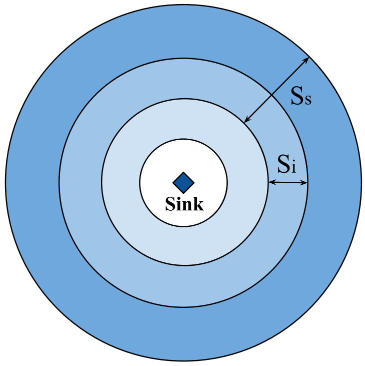
$$E_{gr}^{i} = lE_{elec} = \frac{S_r \rho \lambda}{S_i \rho \mu} E_{elec} = \frac{\pi[(mr)^2 - (ir)^2]\rho\lambda}{\pi[(ir)^2 - ((i-1)r)^2]\rho\mu} E_{elec} = \frac{\lambda(m^2 - i^2)}{\mu(2i-1)} E_{elec} \quad (1 \le i \le m). \tag{5}$$

Here, $S_r \rho \lambda$ represents the data generated by the nodes in area S_r in one unit time. $S_i \rho \mu$ is the number of CH responsible for receiving data in area S_i. Hence, $\frac{S_r \rho \lambda}{S_i \rho \mu}$ is the average data received by each CH in area S_i in one unit time.

We use E_{gs}^{i} to express the average energy consumption of a CH node for transmitting data at layer i in one unit time. In EnergIoT, CHs at layer i not only transmit data generated by themselves, but also forward the data generated by nodes



(a) S_i is in charge of receiving data from nodes in S_r.



(b) S_i is in charge of sending data generated by nodes in S_s.

Fig. 4. Diagram to show areas S_i, S_r, and S_s.

from all outer layers. As shown in Fig. 4(b), nodes in area S_i transmit data generated by nodes from S_s that includes area S_i. Therefore, according to Eq. (3), E_{gs}^i can be calculated as follows:

$$\begin{aligned} E_{gs}^i &= l(E_{elec} + \varepsilon r^\alpha) = \frac{S_s \rho \lambda}{S_i \rho \mu}(E_{elec} + \varepsilon r^\alpha) = \frac{\pi[(mr)^2 - ((i-1)r)^2]\rho\lambda}{\pi[(ir)^2 - ((i-1)r)^2]\rho\mu}(E_{elec} + \varepsilon r^\alpha) \\ &= \frac{\lambda[m^2 - (i-1)^2]}{\mu(2i-1)}(E_{elec} + \varepsilon r^\alpha) \quad (1 \le i \le m). \end{aligned} \tag{6}$$

Here, $S_s \rho \lambda$ represents the data generated by the nodes in area S_s in one unit time. $S_i \rho \mu$ denotes the number of nodes responsible for transmitting data in area S_i. Hence, $\frac{S_s \rho \lambda}{S_i \rho \mu}$ is the average data sent by each CH in area S_i in one unit time.

We denote E_{cl}^i as the average idle listening energy consumption of CH node at layer i in one unit time during *network construction* phase. As described in Section 3.2.1, during the cluster construction, nodes send VH messages to outer layers. Once these nodes send AH message to confirm that they are CHs, they enter into sleep mode. Therefore, we have Eq. (7):

$$E_{cl}^i = \frac{i}{m-1} e_{idle} \qquad 1 \le i \le m. \tag{7}$$

There are $m - 1$ rounds to choose the CHs during network construction phase. Nodes in layer i need to wait for i rounds until they send AH message and enter into sleep mode.

We use E_i to denote the average energy consumption per unit time of a CH node in layer i in EnergIoT, and here we describe it in Eq. (8).

$$\begin{aligned} E_i &= E_{gl}^i + E_{gr}^i + E_{gs}^i + E_{cl}^i + E_{csr}^i = \mu \gamma_i e_{idle} + \frac{\lambda(m^2 - i^2)}{\mu(2i-1)} E_{elec} + \frac{\lambda[m^2 - (i-1)^2]}{\mu(2i-1)}(E_{elec} + \varepsilon r^\alpha) \\ &+ \frac{i}{m-1} e_{idle} + E_{csr}^i \qquad (1 \le i \le m). \end{aligned} \tag{8}$$

Because of the *energy hole* phenomenon, we try to balance the energy consumption among different layers' CH nodes using Eq. (9) to prolong network lifetime.

$$E_i \approx E_{i+1}. \tag{9}$$

It is deserved to notice that, during the *network construction* phase, the number of sending and receiving messages by nodes at different layers is same. The expression by equation is $E_{csr}^i = E_{csr}^{i+1}$, hence the expansion of Eq. (9) is as follows.

$$E_{gl}^i + E_{gr}^i + E_{gs}^i + E_{cl}^i \approx E_{gl}^{i+1} + E_{gr}^{i+1} + E_{gs}^{i+1} + E_{cl}^{i+1}. \tag{10}$$

4.2. Objective: maintaining network performance

In order to guarantee the network performance after introducing EnergIoT, we should keep the same end-to-end delay as that of uniform duty cycle approach. In both of EnergIoT and uniform duty cycle approach, the end-to-end delay consists of the setup latency and the transmission delay. We try to analyze the delay of a packet sent from the outermost layer, because the end-to-end delay of this situation is highest. As we mentioned in Section 3.1, the duty cycle ratios of nodes are controlled by varying the sleep interval T_{sleep}. The active period T_{active} is fixed for each node in order to ensure receiving data packets. Therefore, a node with value of duty cycle γ_i generates a setup latency T_{st} [25]. $T_{st} = T_{sleep}/2K = T_{active}(1-\gamma_i)/2K\gamma_i$, where K is the average number of forwarders each sender have. K is set to 1 according to our structure model in Section 3.1.

We use D_e, D_u to represent the end-to-end delay in EnergIoT and uniform duty cycle ratio approach, respectively. T_{st}^i is the setup latency for layer i, while T_{tran} is the transmission delay of sending a packet from layer i to $i+1$. Therefore, D_e and D_u can be represented as follows:

$$D_e = \sum_{i=1}^{m} T_{st}^i + mT_{tran} = T_{active} \sum_{i=1}^{m} \frac{1-\gamma_i}{2\gamma_i} + mT_{tran}, \tag{11}$$

$$D_u = \sum_{i=1}^{m} T_{st}^i + mT_{tran} = mT_{active} \frac{1-\gamma}{2\gamma} + mT_{tran}. \tag{12}$$

In order to maintain network performance of end-to-end delay in EnergIoT with uniform duty cycle ratios approach, we must make sure that the end-to-end delay in EnergIoT is less than or equal to that in uniform duty cycle ratio approach. Thus, we have Eq. (13):

$$D_e \leqslant D_u \Rightarrow m\frac{1-\gamma}{\gamma} \leqslant \sum_{i=1}^{m} \frac{1-\gamma_i}{\gamma_i}. \tag{13}$$

We can notice density node distribution ρ is canceled out from Eqs. (10) and (13), hence the optimization of energy consumption has nothing to do with ρ.

4.3. Getting value of different duty cycle ratios

In this section, we formulate optimization problem to find the optimal different duty cycle ratios to achieve the objectives mentioned in Sections 4.1 and 4.2. We have two conditions provided in Eqs. (10) and (13) for γ_i. As our prime objective is to improve the energy efficiency, we formulate our objective function based on energy criteria and constraint function based on the end-to-end delay. Therefore, we try to calculate the minimal value of our objective function (Eq. (14)) such that the optimal value of γ_i can satisfy constraint function (Eq. (15)). The constrained optimization problem is expressed as

$$\min_{\gamma_1,\gamma_2,\ldots,\gamma_m} \quad f(\gamma_1,\gamma_2,\ldots,\gamma_m) = \sum_{i=1}^{m} (E_i - E_{i+1})^2, \tag{14}$$

such that

$$m\frac{1-\gamma}{\gamma} \leqslant \sum_{i=1}^{m} \frac{1-\gamma_i}{\gamma_i}. \tag{15}$$

Relying on Lagrange Multiplier [27,28], we find the optimal values for variables $(\gamma_1, \gamma_2, \ldots, \gamma_m)$ and satisfy our constraint at the same time.

We observe that the closer the nodes to the sink, the smaller the the duty cycle ratio. Because the nodes closer to the sink spend more energy to forward and receive the data, they need more time for sleep mode. According to the definition of γ, under the condition of fixed T_{active}, the nodes closer to sink have a smaller value for duty cycle ratios. EnergIoT effectively mitigates the problem of unbalanced energy consumption, which is also demonstrated in our experiments (discussed in Section 5).

5. Simulation analysis

In this section, we carry out extensive simulations to validate the effectiveness of EnergIoT. In particular, we compare EnergIoT with the approach without duty cycle mechanism (we refer this approach as *full-active* approach in the following), as well as the approach with uniform duty cycle ratios (we refer this approach as *uniform* approach in the following). The fixed duty cycle of uniform approach is 2% in the simulation. Our simulation is performed by Castalia Emulator [29] on OMNeT++ platform [30]. The metrics used in the simulation are shown in Table 1.

In the following, we first compare the lifetime of the network in three strategies. Then we show the percentage of remaining energy in different layers of the network for these three approaches. At last, we give a description of the end-to-end delay in different layers of the network. Moreover, we report the average results obtained from 50 simulation experiments and the figures are with 95% confidence interval error bars.

Table 1
Parameters in EnergIoT's simulation scenario.

	Parameter	Value		Parameter	Value
Energy model	E_{elec}	50 nJ/bit	Network model	r	20 m
	α	2		R	200 m
	ε	100 pJ/bit/m^2		m	10
	e_{idle}	0.88 mJ/s		μ	20%
	γ	2%		ρ	60/m^2
	Each node's initial energy	$10.8 * 10^3$ J		λ	400 bps

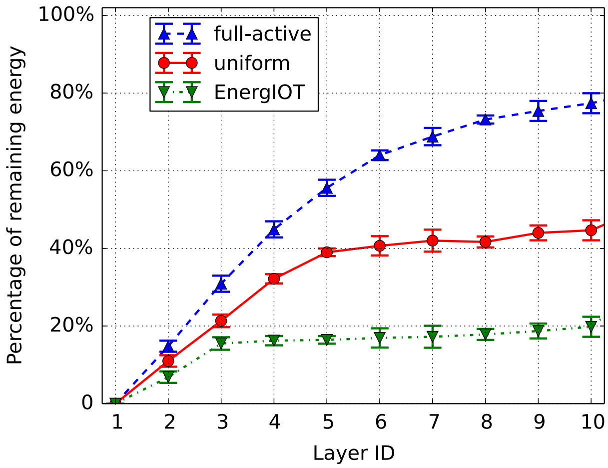


Fig. 5. Comparison of percentage of remaining energy.

5.1. Lifetime analysis

The average lifetime of the network in EnergIoT, *uniform* approach and *full-active* approach is around 361.42 h, 272.87 h and 53.3 h, respectively. The result shows that the approaches deployed with duty cycle could significantly prolong the lifetime of the network. The reason is that, in EnergIoT and *uniform* approach, nodes turn off the sensing function and enter into sleeping mode periodically, which contributes to reducing the energy consumption. However, in *full-active* approach, the nodes closest to sink deplete their energy so quickly that the network ends the life soon. Although the *uniform* approach achieves the aim of energy conservation, it sacrifices the end-to-end delay (details in Section 5.3). Moreover, the network lifetime with EnergIoT strategy extends 32% compared with that of *uniform* approach. Since the energy consumption of nodes in different layers is balanced by introducing different duty cycle ratios, the network will not end prematurely because of *energy hole* phenomenon.

5.2. Energy remaining in different layers

As a result of our experiment, we highlight in Fig. 5 how EnergIoT outperforms the other two approaches in terms of energy efficiency. Indeed, the energy efficiency of a network is given by the percentage of remaining energy in its nodes.

As shown in Fig. 5, the percentage of remaining energy increases with the increasing ID in these three approaches. In both of *uniform* approach and *full-active* approach, the percentage of remaining energy is almost 80% and 45% respectively for most of the layers while the first layer nodes run out of their energy. However, when the layer ID increases, in EnergIoT, the percentage of remaining energy fluctuates around 20% for almost all layers except the first and second layers. We can conclude that the energy consumption is balanced well through different duty cycle ratios. The nodes located at inner layers (closer to the sink) are responsible for receiving and transmitting more traffic loads. If we do not take measure to balance the energy consumption, the inner nodes will deplete energy quickly, which leads to the outer layers' nodes remaining amount of energy (i.e., 45%, 80%). It is a waste for the outer layers' nodes to remain such amount of energy.

In EnergIoT, we deploy different duty cycle ratios for nodes in different layers. In particular, the nodes in the inner layer have smaller duty cycle ratios, which represents that the nodes can sleep more time when it is not in active mode. As we discussed in Eqs. (10) and (13), the energy consumption in different layers is approximately same by tuning the duty cycle ratios. Moreover, the remaining energy of nodes with *full-active* approach is still more or less 80%. The reason for this phenomenon is that the *full-active* approach does not consider turning off the sensing model of nodes. Hence, the inner layers' nodes are easily and quickly run out of their energy.

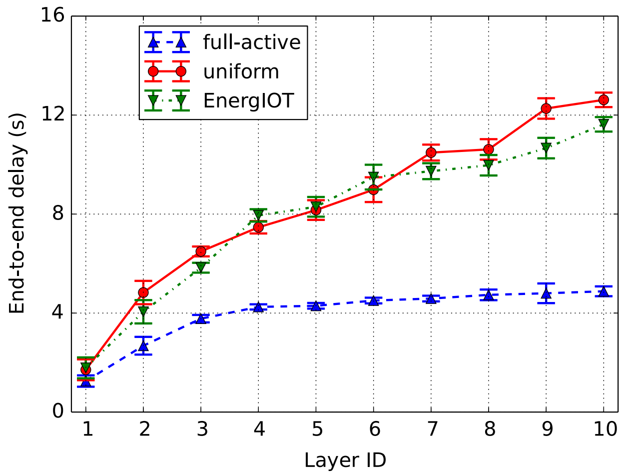


Fig. 6. Comparison of end-to-end delay.

5.3. End-to-end delay analysis

End-to-end delay consists of time to transmit packets from a source to the destination and the latency of setting up duty cycle ratios for different layers' nodes. In our simulation, we report the average end-to-end delay, which represents delay performance. Fig. 6 shows the end-to-end comparison among EnergIoT, *uniform* approach, *full-active* approach.

As shown in Fig. 6, the end-to-end delay of the network with *full-active* approach is less than the network with duty cycle-based approaches. One reason is that, with *full-active* approach, nodes spend all time in the idle listening mode instead of sleeping mode. Therefore, nodes with *full-active* approach can response the traffic once such traffic arrives without wasting much time. The other reason is that, the latency for setting up duty cycle is 0, since γ is 1 (Section 5.3). However, in duty cycle-based approaches, the nodes might be in the sleep mode when the traffic arrives, which means nodes cannot respond immediately to any traffic.

The end-to-end delay in both EnergIoT and *uniform* approach is more or less similar as shown in Fig. 6. We can deduce that EnergIoT achieves the target of extending network lifetime of IoT devices without sacrificing network performance compared to *uniform* approach. The simulation result confirms that EnergIoT efficiently improves network lifetime without prolonging end-to-end delay. In addition, Fig. 6 shows that the nodes located at outer layers have longer end-to-end delay compared with nodes in the inner layers (i.e., the end-to-end delay increases with the increasing ID). EnergIoT is a differential duty cycle approach based on hierarchical clustering architecture. The network is composed of multiple clusters consisting of CH and CNs. The CNs send the packets to their CH directly. Therefore, nodes at outer layers need more forwarders to transmit packets. As a result, the end-to-end delay of nodes at outer layers is larger.

6. Conclusions

In this paper, we proposed EnergIoT, a hierarchical clustering approach, based on different duty cycle ratios to maximize the lifetime of IoT network of battery-powered devices, under the condition of maintaining the network performance. In particular, we assigned the different duty cycle ratios to nodes according to their different distance from the sink. First, the energy consumption of the battery-powered devices are balanced especially for the innermost layer and outermost layer, which avoids the *energy hole* problem. Second, EnergIoT keeps the network performance (i.e., delay) the same as uniform duty cycle approach. Moreover, we modeled the energy consumption considering both *data processing* phase and *network construction* phase based on a hierarchical clustering network structure. We assessed EnergIoT through extensive simulation-based analyses on the OMNet++ platform. The results showed that EnergIoT is feasible and efficient. EnergIoT is able to improve the lifetime of IoT network by 32%, when compared to the approach applied with uniform duty cycle, without degrading the network performance.

In the future, we will further investigate the impact of each component on the overall performance in terms of energy consumption and delay reduction. In particular, we intend to run ad-hoc simulations to adjust the percentage of CHs in a network. Moreover, we would like to evaluate the efficiency of our proposal in a real-world IoT testbed.

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