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Energy-Balanced Transmission With Accurate Distances for Strip-Based Wireless Sensor Networks

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ABSTRACT An obvious limitation of wireless sensor networks (WSNs) concerns the energy consumption and the network lifetime. Transmitting signals, including sending and receiving, take most of the energy dissipation in such a network. Generally the data transmission in such a network follows a many-to-one pattern, which leads to the so-called energy hole near the sink and lifetime reduction. This paper makes a first attempt to solve the many-to-one transmission problem of strip-based WSN and avoid energy holes of such a network, which is divided into multiple layers. Specifically, we propose an accurate-distances-based transmission scheme, which aims at achieving the most precise layer lengths so far and obtaining the optimal transmission distances in different regions to date. Such a transmission scheme enables the network lifetime of the strip-based WSN to reach a maximum. Extensive simulations are carried out to validate the effectiveness and advantages of our transmission scheme.

INDEX TERMS Strip-based wireless sensor networks, energy hole, transmission scheme, accurate distance.

I. INTRODUCTION

Wireless sensor networks (WSNs) generally consist of a large number of sensor nodes, which are constrained by limitations in energy resources, processing ability, storage capability, and radio communication range, etc [1], [2]. As the foundation, key components, and important network technologies of the Internet of Things (IoT) [3]–[8], WSNs have a wide range of military and civilian applications [1], [2], such as such as environment surveillance, health care, military battlefield, agriculture monitoring, industrial control, and smart life. With the application requirements of WSNs being lifted, the application difference and environment diversity must be taken into account in the design of WSNs.

Due to limited power supply and impossible or inconvenient recharging of the battery of nodes, the design of WSNs must aim to maximize network lifetime with efficient energy utilization. Generally the many-to-one transmission pattern is adopted in WSNs, where sensor nodes closer to the sink or base station have to transmit more packets than those far away. This easily leads to the phenomenon of energy hole. Related research has indicated that there is still up to 90% residue energy in WSNs when the network has died due to the phenomenon [13], [14]. Thus, effective load balancing approaches must be designed for such networks.

Wireless power transfer is a potential solution to lengthen the lifetime of WSNs, such as mechanical energy recharging [11] and biomechanical energy recharging [12]. However, frequent battery recharging is apt to cause difficulties in creating and collecting production information, and in making instant cyber-physical decisions in the current industry framework [13]. So in order to avoid frequent wireless recharging, the battery energy should be carefully used, and the network lifetime is still one of the most important factors in WSNs.

It is regarded that radio is the main consumer of energy in WSNs [14], [15]. According to the widely-adopted First-Order Radio Model in [16], energy consumption in wireless communications is chiefly determined by the transmission distance and the data amount. Therefore, transmission distance control and data traffic distribution constitute an important approach to minimize energy consumption and maximize network lifetime.

Many researchers have studied the many-to-one transmission methods of WSNs. These methods are generally divided into two classes, namely hybrid transmission and power adjustment. In hybrid transmission such as that in [17]–[22], nodes adopt two types of transmission patterns, i.e. direct transmission to the sink and hop-by-hop transmission, so as to achieve load equilibrium. In power adjustment, such as that in [23]–[28], each node adopts only one type of transmission pattern, but nodes on different locations use different transmission distances for the purpose of energy consumption equilibrium.

A. MOTIVATIONS

The above transmission strategies have apparent limitations, which are summarized as follows.

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1) Almost all the above transmission strategies can only be applied to corona network models or circular network scenarios, and cannot been applied to network scenarios concerning other shapes, such as strip-based regions, including mines, railways, rivers, bridges, and metros, etc. In other words, the application scope of transmission schemes for WSNs needs to be further expanded.
2) There are many transmission protocols for WSNs, such as that in [22]–[25], in which it is generally agreed that the transmission distance near the sink should be shorter than that far from the sink for the aim of energy consumption balancing. However, the usual term ''shorter'' is too vague to guide the data transmission. In certain energy consumption conditions of WSNs, accuracy should be as high as possible [29].
3) Due to the lack of precise value of transmission distance, the optimal transmission distance at each position of the network may fail to appear. Therefore, the optimal relationship between transmission distance and node position needs to be accurately defined and well proved.

B. MAIN CONTRIBUTIONS

Motivated by the above analysis, we put forward an accurate-distances-based transmission scheme (ADTS) for strip-based WSNs. The main contributions of our work are outlined as follows.

1) To the best of our knowledge, this is the first time that the transmission problem is specially targeting strip-based WSNs and well solved. This expands the application ranges and scenarios of WSNs, including mines, railways, rivers, bridges, and metros, etc., as shown in Fig. 1.

FIGURE 1. Application scenarios of the strip-based WSNs.

2) To date, the most accurate layer lengths of the network and the optimal transmission distances in different places are achieved by theoretical calculation and optimization. This facilitates the network construction and data transmission of strip-based WSNs.
3) As far as we know, currently this is the optimal relationship between transmission distance and node position, which are definitely defined and well proved for strip-based WSNs. This contributes to reaching the maximum lifetime of such networks.
4) We prove that, it is impossible to achieve completely balanced energy depletion among all the nodes of the strip-based WSNs in most cases, and only nearly balanced energy depletion in the network is achievable. However, if the length of the strip-based network just satisfies a specific condition, completely balanced energy depletion among all the nodes is still attainable.

C. ORGANIZATION

The remainder of the paper is structured as follows. Section II is devoted to literature review. The system model is described in Section III. Section IV introduces the details of the proposed transmission scheme. In Section V, the performances of the scheme are assessed by simulation results. Finally, the paper is concluded in Section VI.

II. RELATED WORK

There are various types of load balancing strategies for WSNs, such as node deployment, data transmission, and operation scheduling. The following is the state-of-the-art research in terms of data transmission of WSNs, which provides solutions to resolve the many-to-one issue in such networks.

A. HYBRID TRANSMISSION

Olariu and Stojmenovic [17] study the concentric corona network model and discuss the relationship between the network lifetime and the width of each corona of the network model. It's concluded that all coronas must have the same width and nodes in the same corona should forward data to the adjacent inner corona so as to minimize the total energy consumption of the network. This transmission manner could cause different energy expenditure among all coronas due to the data-traffic difference among disparate coronas.

Perillo *et al*. [18] put forward a transmission scheme alternating between single-hop communication and multi-hop communication periodically. It is considered that energy holes exist in two situations. In the first case, data is sent directly to the sink and nodes farther away from the sink would deplete their energy faster. In the second context, data is delivered to the sink through multiple hops and nodes close to the sink suffer from more traffic load. It is assumed that each node can adjust its transmission range and the network lifetime maximization is explored as a linear optimization problem.

Jarry *et al*. [19] present a mixed and distributed data transmission algorithm for energy consumption balancing in the entire network. The mixed routing strategy allows each sensor node to either send a message to one of its immediate neighbors, or to directly communicate with the sink, with the decision being based on a potential function with regard to its remaining energy. By using a linear programming description of the message flow, they prove that an energy-balanced mixed strategy beats every other possible routing strategy in terms of lifespan maximization.

Efthymiou *et al*. [20] propose a transmission algorithm by which the decision is made in each step whether to propagate data one-hop towards the sink, or to send data directly to the sink. This randomized choice balances the one-hop transmission with the direct transmission to the sink, which are more expensive but "bypass" the sensors lying close to the sink. The authors also estimate the probabilities for each propagation choice in order to guarantee energy balance.

Zhang and Shen [21] formulate the energy balance problem as the problem of optimal data allocation by combining the ideas of corona-based network division and mixed-routing strategy together with data aggregation. Based on the corona-based model, the authors present an energy-balanced transmission protocol EBDG, in which all nodes in the same corona use the same probability for direct transmission and the same probability for hop-by-hop transmission.

Based on concentric rings around the sink, Azad and Kamruzzaman [22] decompose the transmission distance of traditional multi-hop scheme into two parts: ring thickness and hop size. The authors propose three transmission policies called fixed hop size, synchronous variable hop size, and asynchronous variable hop size transmissions. These transmission policies differ in terms of their degree of flexibility in using variable transmission ranges and their associated duty cycles.

B. POWER ADJUSTMENT

Tran-Quang and Miyoshi [23] formulate the transmission range adjustment optimization problem as a 0-1 multiple choice knapsack problem, and propose a dynamic programming method to solve such an optimization problem for uniformly deployed WSNs. The proposed algorithm allows sensor nodes to adjust their individual transmission levels dynamically, according to their residual energy.

Chen *et al*. [24] present a data transmission strategy where each node will be helped by the nodes at its previous hop through a cooperative method. During the period of cooperation, each node helps its relay node at the next hop to forward data through a cooperative multi-input single-output way and the energy burden of each corona is shared by the outer corona to a certain extent.

Song *et al*. [25] investigate the concentric coronas model and prove that searching the optimal transmission distance is a multiple-objective and NP-hard problem. Furthermore, the authors present a centralized algorithm and a distributed algorithm for assigning the transmission ranges for nodes of each corona. The two algorithms obtain results approximated to the optimal solution.

In order to achieve high energy efficiency and good energy balancing, a transmission scheme named UMM [26] with two strategies of energy balancing is proposed to solve this problem and maximize the network lifetime. This algorithm uses ant colony optimization and includes two inter-related energy-balancing approaches so as to expand the lifetime of the network. In UMM, the ant just needs to move one step to complete the full trip, and the heuristic information is removed in the transition probability of the ant.

By using ant colony optimization, an optimal-distance based transmission strategy (ODTS) [27] is put forward on the basis of the corona network model. A local optimal-distance achievement mechanism and a global optimal-distance acquirement scheme are developed to determine the transmission distances of different places. The goal is to achieve energy expenditure balancing and energy depletion minimization throughout the network.

Another transmission range adjustment strategy, named multilevel minimization and balancing for energy consumption (MMBEC) [28], is put forward to select a suitable transmission range of nodes in different locations. In such a strategy, transmission range is selected on the basis of the so-called reference transmission distance, in which energy depletion minimization and energy consumption equilibrium are jointly considered and fully reflected to realize the objective of network lifespan maximization.

III. SYSTEM MODEL

A. NETWORK MODEL

We assume that a large number of static sensor nodes are randomly and uniformly deployed on a strip area, the length of which is L and the width of which is H, as shown in Fig. 2. Considering the practical application environment, we set $L \gg H$. We suppose that sensor nodes with density ρ can generate data at a speed of b bits per transmission round. We assume that each node has the same initial energy E_0.

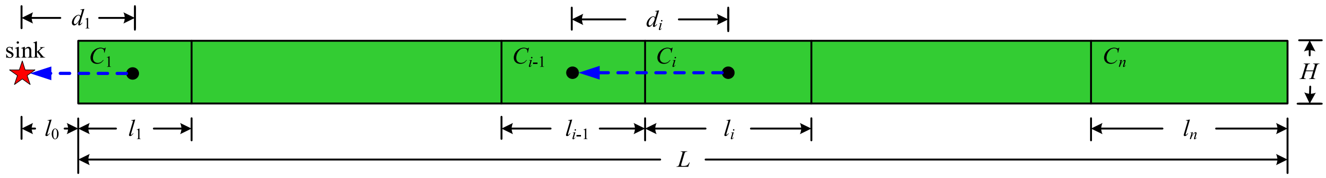

FIGURE 2. Network model.

Due to lots of advantages of clustering in WSNs [30], [31], the network is divided into n layers, which are regarded as n clusters, denoted as $C_1, C_2, C_3, \ldots, C_n$, respectively. Correspondingly, the length of each of those clusters is denoted as $l_1, l_2, l_3, \ldots, l_n$, respectively. There is a cluster head (CH) in every cluster and the CH rotates with an equal probability in the same cluster. A static sink with infinite energy is located on one end of the network.

The CH performs the following tasks: 1) data gathering from other nodes of the same cluster; 2) data fusion in the same cluster with fuse rate $1/\beta$, i.e. the ratio of data received to data delivered; and 3) data delivery from a cluster to its adjacent one in the direction of the sink.

B. RADIO MODEL

In this work, we use the typical radio model mentioned in [16], where the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. To transmit an l-bit message over a distance d, the transmission radio and the reception radio are respectively

$$E_{Tx}(l,d) = \begin{cases} le_{elec} + l\varepsilon_{fs}d^2, d < d_0 \\ le_{elec} + l\varepsilon_{amp}d^4, d \geq d_0 \end{cases} \quad (1)$$

and

$$E_{Rx}(l) = le_{elec} \quad (2)$$

where $e_{elec} = 5 \times 10^{-8}$J/bit, $\varepsilon_{fs} = 10^{-11}$J/bit/m^2, $\varepsilon_{amp} = 1.3 \times 10^{-15}$J/bit/m^4. d_0 ($d_0 = 87$m) is the boundary between the free space model and the multipath model. For the energy depletion minimum, we select the free space model. Similar to that in [21], [26], and [27], any potential overhead at the MAC layer is omitted because that the data traffic is much larger than the control traffic.

C. PROBLEM DESCRIPTION

As mentioned above, data is delivered from one cluster to another, more specifically, from one CH to another, in the direction of the sink. The transmission distance of cluster C_i is denoted as c, i.e. the distance between the CH of C_i and that of C_{i-1}, as shown in Fig. 2. The lifetime of any cluster C_i is also denoted as T_i. The network lifetime is determined by the minimum one of all clusters, so our main goal is to

$$\begin{aligned} &\max\min \quad T_i \\ &\text{s.t. } i = 1, 2, 3 \ldots n \\ &\quad 0 < l_i \leq L, \\ &\quad \sum_{i=1}^{n} l_i = L \end{aligned} \quad (3)$$

In order to achieve the above goal, our work is to obtain the optimal values of the following key factors: 1) $l_i(i = 1, 2, \cdots, n)$, i.e. the length of each layer C_i; and 2) $d_i(i = 1, 2, \cdots, n)$, i.e. the transmission distance of nodes on every layer C_i.

IV. TRANSMISSION SCHEME BASED ON ACCURATE DISTANCES

In such networks, data transmission is performed through two manners: 1) intra-cluster communication, which adopts single-hop manner, i.e. data is delivered from each node to its CH; and 2) inter-cluster communication, which uses multiple-hop fashion, i.e. data is delivered from a CH to its adjacent one towards the sink. The solution processes of the key factors are described as follows.

A. ENERGY DEPLETION OF INTRA-CLUSTER COMMUNICATIONS

Since $L \gg H$ as shown in Fig. 2, the distance between any two nodes of the same cluster is approximately equal to that between their projection points. For example, the distance between point A and point B is approximately equal to that from point A' to point B' in Fig. 3. Here point A' and point B' are respectively the projection of point A and point B in the direction of the length of the network.

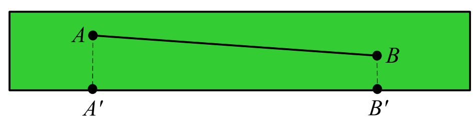

FIGURE 3. The approximate distance of intra-cluster communications.

Thus, the expectation of the distance square between any two nodes in layer C_i is

$$\begin{aligned} \mathrm{E}\left[d^2\right] &= \int_0^{l_i}\int_0^{l_i}(x-y)^2\frac{1}{l_i^2}\mathrm{d}x\mathrm{d}y \\ &= \int_0^{l_i}\left(\frac{l_i}{3}+\frac{y^2}{l_i^2}-y\right)\mathrm{d}y \\ &= \frac{l_i^2}{6} \end{aligned} \quad (4)$$

which is approximately equal to the average distance square from the CH to any node of the cluster.

In any cluster C_i, intra-cluster energy consumption E_i^{intra} includes two parts: 1) $E_i^{\text{intra-tr}}$, energy of data transmission by ordinary nodes of the cluster; and 2) $E_i^{\text{intra-re}}$, energy of data reception by the CH of the cluster.

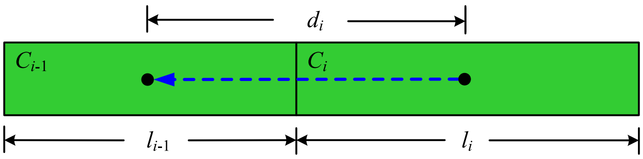

FIGURE 4. The average distance of inter-cluster communications.

In any cluster C_i, the data delivered by ordinary nodes of this cluster is

$$S_i^{\text{intra}} = l_i H \rho b \tag{5}$$

which is equal to the data received by the CH of this cluster, i.e.

$$\begin{aligned} R_i^{\text{intra}} &= S_i^{\text{intra}} \\ &= l_i H \rho b \end{aligned} \tag{6}$$

According to Eq. (1), in the course of intra-cluster communications, the energy consumption of data transmission by ordinary nodes of the cluster is

$$\begin{aligned} E_i^{\text{intra-tr}} &= S_i^{\text{intra}} \left(e_{\text{elec}} + \varepsilon_{\text{fs}} E\left[d^2\right]\right) \\ &= l_i H \rho b \left(e_{\text{elec}} + \varepsilon_{\text{fs}} \frac{l_i^2}{6}\right) \\ &= l_i H \rho b e_{\text{elec}} + \varepsilon_{\text{fs}} \frac{H \rho b l_i{}^3}{6} \end{aligned} \tag{7}$$

and according to Eq. (2), the energy consumption of data reception by the CH of the cluster is

$$\begin{aligned} E_i^{\text{intra-re}} &= R_i^{\text{intra}} e_{\text{elec}} \\ &= l_i H \rho b e_{\text{elec}} \end{aligned} \tag{8}$$

Therefore, according to Eq. (7) and Eq. (8), the energy consumption of intra-cluster communication in cluster C_i can be obtained as follows.

$$\begin{aligned} E_i^{\text{intra}} &= E_i^{\text{intra-re}} + E_i^{\text{intra-tr}} \\ &= l_i H \rho b e_{\text{elec}} + l_i H \rho b e_{\text{elec}} + \varepsilon_{\text{fs}} \frac{H \rho b l_i{}^3}{6} \\ &= 2 l_i H \rho b e_{\text{elec}} + \varepsilon_{\text{fs}} \frac{H \rho b l_i{}^3}{6} \end{aligned} \tag{9}$$

B. ENERGY DEPLETION OF INTER-CLUSTER COMMUNICATIONS

In the course of inter-cluster communications, data is delivered from a CH to its adjacent one. Considering the equal-probability rotation mechanism of CHs, the expectation of the transmission distance of the CH of cluster C_i is

$$[d_i] = \frac{l_{i-1} + l_i}{2} \tag{10}$$

which can be revealed by Fig. 4.

1) CASE 1: THE MIDDLE LAYERS ($1 < i < n$)

If $1 < i < n$, the data received by the CH of cluster C_i, i.e. the one delivered from cluster C_{i+1} to C_i, is

$$R_i^{\text{inter}} = \frac{(L - \sum_{x=1}^{i} l_x) H \rho b}{\beta} \tag{11}$$

and the data delivered from the CH of cluster C_i to that of cluster C_{i-1} is

$$S_i^{\text{inter}} = \frac{(L - \sum_{x=1}^{i-1} l_x) H \rho b}{\beta} \tag{12}$$

According to Eq. (2), during the process of inter-cluster communications, the energy consumption of data reception of cluster C_i is

$$\begin{aligned} E_i^{\text{inter-re}} &= R_i^{\text{inter}} e_{\text{elec}} \\ &= \frac{(L - \sum_{x=1}^{i} l_x) H \rho b}{\beta} e_{\text{elec}} \end{aligned} \tag{13}$$

and according to Eq. (1), the energy consumption of data transmission of cluster C_i is

$$\begin{aligned} E_i^{\text{inter-tr}} &= S_i^{\text{inter}} \left(e_{\text{elec}} + \varepsilon_{\text{fs}} d_i^2 \right) \\ &= \frac{(L - \sum_{x=1}^{i-1} l_x) H \rho b}{\beta} \left[e_{\text{elec}} + \varepsilon_{\text{fs}} \left(\frac{l_{i-1} + l_i}{2} \right)^2 \right] \end{aligned} \tag{14}$$

Hence, we can get the following energy expenditure of inter-cluster communications of this cluster

$$\begin{aligned} E_i^{\text{inter}} &= E_i^{\text{inter-re}} + E_i^{\text{inter-tr}} \\ &= \frac{(L - \sum_{x=1}^{i} l_x) H \rho b}{\beta} e_{\text{elec}} \\ &\quad + \frac{(L - \sum_{x=1}^{i-1} l_x) H \rho b}{\beta} \left[e_{\text{elec}} + \varepsilon_{\text{fs}} \left(\frac{l_{i-1} + l_i}{2} \right)^2 \right] \\ &= \frac{2(L - \sum_{x=1}^{i} l_x) H \rho b}{\beta} e_{\text{elec}} + \frac{(L - \sum_{x=1}^{i-1} l_x) H \rho b}{\beta} e_{\text{elec}} \\ &\quad + \frac{\varepsilon_{\text{fs}} (L - \sum_{x=1}^{i-1} l_x) H \rho b (l_{i-1} + l_i)^2}{4\beta} \end{aligned} \tag{15}$$

2) CASE 2: THE FIRST LAYER ($i = 1$)

If $i = 1$, data is delivered directly to the sink. The data received by the CH of this cluster, i.e. the one delivered from cluster C_2 to C_1, is

$$R_1^{\text{inter}} = \frac{(L - l_1) H \rho b}{\beta} \tag{16}$$

and the data transmitted by the CH of cluster C_1 is

$$S_1^{\text{inter}} = \frac{LH\rho b}{\beta} \tag{17}$$

Moreover, the average transmission distance of the CH of cluster C_1 is

$$[d_1] = l_0 + \frac{l_1}{2} \tag{18}$$

According to Eq. (2), during the process of inter-cluster communications, the energy consumption of data reception of cluster C_1 is

$$\begin{aligned} E_1^{\text{inter-re}} &= R_1^{\text{inter}} e_{\text{elec}} \\ &= \frac{(L-l_1)H\rho b}{\beta} e_{\text{elec}} \end{aligned} \tag{19}$$

and according to Eq. (1), the energy consumption of data transmission of cluster C_1 is

$$\begin{aligned} E_1^{\text{inter-tr}} &= S_1^{\text{inter}} \left(e_{\text{elec}} + \varepsilon_{\text{fs}} d_1^2\right) \\ &= \frac{LH\rho b}{\beta}\left[e_{\text{elec}} + \varepsilon_{\text{fs}}\left(l_0 + \frac{l_1}{2}\right)^2\right] \end{aligned} \tag{20}$$

Therefore, by incorporating data transmitting and data reception, we can get the following energy expenditure of inter-cluster communications of cluster C_1

$$\begin{aligned} &E_1^{\text{inter}} \\ &= E_1^{\text{inter-re}} + E_1^{\text{inter-tr}} \\ &= \frac{(L-l_1)H\rho b}{\beta} e_{\text{elec}} + \frac{LH\rho b}{\beta}\left[e_{\text{elec}} + \varepsilon_{\text{fs}}\left(l_0 + \frac{l_1}{2}\right)^2\right] \\ &= \frac{2(L-l_1)H\rho b}{\beta} e_{\text{elec}} + \frac{l_1 H\rho b}{\beta} e_{\text{elec}} + \frac{\varepsilon_{\text{fs}} LH\rho b}{\beta}\left(l_0 + \frac{l_1}{2}\right)^2 \end{aligned} \tag{21}$$

3) CASE 3: THE LAST LAYER ($i = n$)

If $i = n$, the CH of cluster C_n doesn't receive data from other clusters, i.e.

$$R_n^{\text{inter}} = 0 \tag{22}$$

and the data transmitted by the CH of this cluster is

$$S_n^{\text{inter}} = \frac{(L - \sum_{x=1}^{n-1} l_x)H\rho b}{\beta} \tag{23}$$

Moreover, the average transmission distance of the CH of this cluster is

$$[d_n] = \frac{l_{n-1} + l_n}{2} \tag{24}$$

According to Eq. (2), during the process of inter-cluster communications, the energy consumption of data reception of this cluster is

$$\begin{aligned} E_{\text{n}}^{\text{inter-re}} &= R_{\text{n}}^{\text{inter}} e_{\text{elec}} \\ &= 0 \end{aligned} \tag{25}$$

and according to Eq. (1), the energy consumption of data transmission of this cluster is

$$\begin{aligned} E_n^{\text{inter-tr}} &= S_n^{\text{inter}} \left(e_{\text{elec}} + \varepsilon_{\text{fs}} d_n^2\right) \\ &= \frac{(L - \sum_{x=1}^{n-1} l_x)H\rho b}{\beta}\left[e_{\text{elec}} + \varepsilon_{\text{fs}}\left(\frac{L - \sum_{x=1}^{n-2} l_x}{2}\right)^2\right] \end{aligned} \tag{26}$$

Hence, we can get the following energy expenditure of inter-cluster communications of cluster C_n

$$\begin{aligned} E_n^{\text{inter}} &= E_n^{\text{inter-re}} + E_n^{\text{inter-tr}} \\ &= \frac{(L - \sum_{x=1}^{n-1} l_x)H\rho b}{\beta}\left[e_{\text{elec}} + \varepsilon_{\text{fs}}\left(\frac{L - \sum_{x=1}^{n-2} l_x}{2}\right)^2\right] \\ &= \frac{\varepsilon_{\text{fs}}(L - \sum_{x=1}^{n-1} l_x)H\rho b}{4\beta}\left(L - \sum_{x=1}^{n-2} l_x\right)^2 \\ &\quad + \frac{(L - \sum_{x=1}^{n-1} l_x)H\rho b}{\beta} e_{\text{elec}} \end{aligned} \tag{27}$$

C. AVERAGE ENERGY DEPLETION OF INDIVIDUAL NODES

1) CASE 1: THE MIDDLE LAYERS ($1 < i < n$)

If $1 < i < n$, according to Eq. (9) and Eq. (15), the total energy consumption of cluster C_i is

$$\begin{aligned} E_i^{\text{total}} &= E_i^{\text{intra}} + E_i^{\text{inter}} \\ &= \frac{2(L - \sum_{x=1}^{i} l_x)H\rho b}{\beta} e_{\text{elec}} + 2l_i H\rho b e_{\text{elec}} + \varepsilon_{\text{fs}} \frac{H\rho b l_i^3}{6} \\ &\quad + \frac{\varepsilon_{\text{fs}}(L - \sum_{x=1}^{i-1} l_x)H\rho b\,(l_i + l_{i-1})^2}{4\beta} + \frac{l_i H\rho b}{\beta} e_{\text{elec}} \\ &= \frac{2(L - \sum_{x=1}^{i} l_x)H\rho b}{\beta} e_{\text{elec}} + \frac{(1+2\beta)l_i H\rho b}{\beta} e_{\text{elec}} \\ &\quad + \frac{\varepsilon_{\text{fs}}(L - \sum_{x=1}^{i-1} l_x)H\rho b\,(l_i + l_{i-1})^2}{4\beta} + \varepsilon_{\text{fs}} \frac{H\rho b l_i^3}{6} \end{aligned} \tag{28}$$

and the number of nodes of this cluster is

$$N_i = l_i H\rho \tag{29}$$

So the average energy consumption of individual nodes (AECIN) of this cluster is

$$\begin{aligned}
\bar{E_i} &= \frac{E_i^{\text{total}}}{N_i} \\
&= \frac{\frac{2(L-\sum_{x=1}^{i} l_x)H\rho b}{\beta}e_{\text{elec}} + \frac{(1+2\beta)l_i H\rho b}{\beta}e_{\text{elec}}}{l_i H\rho} \\
&\quad + \frac{\frac{\varepsilon_{\text{fs}}(L-\sum_{x=1}^{i-1} l_x)H\rho b(l_i+l_{i-1})^2}{4\beta} + \varepsilon_{\text{fs}}\frac{H\rho b{l_i}^3}{6}}{l_i H\rho} \\
&= \frac{2(L-\sum_{x=1}^{i} l_x)b}{\beta l_i}e_{\text{elec}} + \frac{(1+2\beta)b}{\beta}e_{\text{elec}} \\
&\quad + \frac{\varepsilon_{\text{fs}}(L-\sum_{x=1}^{i-1} l_x)b\,(l_i+l_{i-1})^2}{4\beta l_i} + \varepsilon_{\text{fs}}\frac{b{l_i}^2}{6} \qquad (30)
\end{aligned}$$

2) CASE 2: THE FIRST LAYER ($i = 1$)

If $n = 1$, according to Eq. (9) and Eq. (21), the total energy consumption of cluster C_1 is

$$\begin{aligned}
E_1^{\text{total}} &= E_1^{\text{intra}} + E_1^{\text{inter}} \\
&= \frac{2\,(L-l_1)\,H\rho b}{\beta}e_{\text{elec}} + \frac{\varepsilon_{\text{fs}}LH\rho b}{\beta}\left(l_0 + \frac{l_1}{2}\right)^2 \\
&\quad + 2l_1 H\rho b e_{\text{elec}} + \varepsilon_{\text{fs}}\frac{H\rho b{l_1}^3}{6} + \frac{l_1 H\rho b}{\beta}e_{\text{elec}} \\
&= \varepsilon_{\text{fs}}\frac{H\rho b{l_1}^3}{6} + \left(2e_{\text{elec}} - \frac{e_{\text{elec}}}{\beta} + \frac{\varepsilon_{\text{fs}}Ll_0}{\beta}\right)H\rho b l_1 \\
&\quad + \frac{2LH\rho b}{\beta}e_{\text{elec}} + \frac{\varepsilon_{\text{fs}}LH\rho b}{\beta}l_0^2 + \frac{\varepsilon_{\text{fs}}LH\rho b}{4\beta}l_1^2 \qquad (31)
\end{aligned}$$

and the number of nodes of this cluster is

$$N_1 = l_1 H\rho \qquad (32)$$

So the AECIN of this cluster is

$$\begin{aligned}
\bar{E_1} &= \frac{E_1^{\text{total}}}{N_1} \\
&= \frac{\varepsilon_{\text{fs}}\frac{H\rho b{l_1}^3}{6} + \left(2e_{\text{elec}} - \frac{e_{\text{elec}}}{\beta} + \frac{\varepsilon_{\text{fs}}Ll_0}{\beta}\right)H\rho b l_1}{l_1 H\rho} \\
&\quad + \frac{\frac{2LH\rho b}{\beta}e_{\text{elec}} + \frac{\varepsilon_{\text{fs}}LH\rho b}{\beta}l_0^2 + \frac{\varepsilon_{\text{fs}}LH\rho b}{4\beta}l_1^2}{l_1 H\rho} \\
&= \varepsilon_{\text{fs}}\frac{b{l_1}^2}{6} + \frac{\varepsilon_{\text{fs}}Lb}{4\beta}l_1 + \left(2e_{\text{elec}} - \frac{e_{\text{elec}}}{\beta} + \frac{\varepsilon_{\text{fs}}Ll_0}{\beta}\right)b \\
&\quad + \frac{\left(2e_{\text{elec}} + \varepsilon_{\text{fs}}l_0^2\right)Lb}{\beta l_1} \qquad (33)
\end{aligned}$$

3) CASE 3: THE LAST LAYER ($i = n$)

If $i = n$, according to Eq. (9) and Eq. (27), the total energy consumption of cluster C_n is

$$\begin{aligned}
E_n^{\text{total}} &= E_n^{\text{intra}} + E_n^{\text{inter}} \\
&= \frac{(L-\sum_{x=1}^{n-1} l_x)H\rho b}{\beta}e_{\text{elec}} + \varepsilon_{\text{fs}}\frac{H\rho b\left(L-\sum_{x=1}^{n-1} l_x\right)^3}{6} \\
&\quad + \frac{\varepsilon_{\text{fs}}(L-\sum_{x=1}^{n-1} l_x)H\rho b}{4\beta}\left(L-\sum_{x=1}^{n-2} l_x\right)^2 \\
&\quad + 2(L-\sum_{x=1}^{n-1} l_x)H\rho b e_{\text{elec}} \qquad (34)
\end{aligned}$$

and the number of nodes of this cluster is

$$N_n = l_n H\rho \qquad (35)$$

So the AECIN of this cluster is

$$\begin{aligned}
\bar{E_n} &= \frac{E_n^{\text{total}}}{N_n} \\
&= \frac{\frac{(L-\sum_{x=1}^{n-1} l_x)H\rho b}{\beta}e_{\text{elec}} + \varepsilon_{\text{fs}}\frac{H\rho b\left(L-\sum_{x=1}^{n-1} l_x\right)^3}{6}}{(L-\sum_{x=1}^{n-1} l_x)H\rho} \\
&\quad + \frac{\frac{\varepsilon_{\text{fs}}(L-\sum_{x=1}^{n-1} l_x)H\rho b}{4\beta}\left(L-\sum_{x=1}^{n-2} l_x\right)^2}{(L-\sum_{x=1}^{n-1} l_x)H\rho} \\
&\quad + \frac{2(L-\sum_{x=1}^{n-1} l_x)H\rho b e_{\text{elec}}}{(L-\sum_{x=1}^{n-1} l_x)H\rho} \\
&= \frac{b}{\beta}e_{\text{elec}} + \frac{\varepsilon_{\text{fs}}b}{4\beta}\left(L-\sum_{x=1}^{n-2} l_x\right)^2 + 2be_{\text{elec}} \\
&\quad + \varepsilon_{\text{fs}}\frac{b(L-\sum_{x=1}^{n-1} l_x)^2}{6} \qquad (36)
\end{aligned}$$

D. THE OPTIMAL LENGTH AND TRANSMISSION DISTANCE OF EACH LAYER

1) CASE 1: THE FIRST LAYER ($i = 1$)

In order to maximize the network lifetime, we minimize the average energy consumption of cluster C_1 and accordingly obtain the corresponding length of layer C_1. After that, we make the average energy consumption of other individual layers be equal or less than that of layer C_1. Thus the above-mentioned length of layer C_1 is the optimal one.

To find the minimum value of the average energy consumption of cluster C_1, we compute the first derivative of Eq. (33)

$$\frac{d\bar{E}_1}{dl_1} = -\frac{\left(2e_{\text{elec}} + \varepsilon_{\text{fs}} l_0^2\right) Lb}{\beta l_1^2} + \frac{\varepsilon_{\text{fs}} Lb}{4\beta} + \varepsilon_{\text{fs}} \frac{bl_1}{3} \tag{37}$$

and make it equal to zero, i.e.

$$\frac{d\bar{E}_1}{dl_1} = 0 \tag{38}$$

Then we get the following factors, 1) l_1, the optimal length of layer C_1; and 2) d_1, the optimal transmission distance of layer C_1.

$$\begin{cases} l_1 = \omega + \frac{L^2}{16\omega\beta^2} - \frac{L}{4\beta} \\ d_1 = l_0 + \frac{l_1}{2} \\ \omega = \sqrt[3]{\sqrt{u - \left(\frac{L}{4\beta}\right)^6} - u} \\ u = \left[\left(\frac{L}{4\beta}\right)^3 - \frac{3L\left(2e_{\text{elec}} + \varepsilon_{\text{fs}} l_0^2\right)}{2\beta\varepsilon_{\text{fs}}}\right]^2 \end{cases} \tag{39}$$

Moreover, we get the following $\bar{E}_{1\min}$, the minimum value of AECIN of layer C_1

$$\begin{cases} \bar{E}_{1\min} = \frac{2Lb}{\beta l_1} e_{\text{elec}} + 2\left(1 + \frac{1}{\beta}\right) be_{\text{elec}} + \frac{\varepsilon_{\text{fs}} Lb}{\beta} l_1 \\ \qquad + \left(\frac{1}{6} - \frac{1}{2\beta}\right) \varepsilon_{\text{fs}} b l_1{}^2 \\ l_1 = \omega + \frac{L^2}{16\omega\beta^2} - \frac{L}{4\beta} \\ \omega = \sqrt[3]{\sqrt{u - \left(\frac{L}{4\beta}\right)^6} - u} \\ u = \left[\left(\frac{L}{4\beta}\right)^3 - \frac{3L\left(2e_{\text{elec}} + \varepsilon_{\text{fs}} l_0^2\right)}{2\beta\varepsilon_{\text{fs}}}\right]^2 \end{cases} \tag{40}$$

2) CASE 2: THE MIDDLE LAYERS ($1 < i < n$)

For the sake of network lifetime maximization, we make the AECIN of any other layer be equal to the minimum one of layer C_1, i.e. according to Eq. (30) and Eq. (40), we get

$$\begin{aligned} \bar{E}_{1\min} &= \bar{E}_i \\ &= \frac{2(L - \sum_{x=1}^{i-1} l_x - l_i)b}{\beta l_i} e_{\text{elec}} + \frac{(1 + 2\beta)b}{\beta} e_{\text{elec}} \\ &\quad + \frac{\varepsilon_{\text{fs}}(L - \sum_{x=1}^{i-1} l_x) b \left(l_i + l_{i-1}\right)^2}{4\beta l_i} + \varepsilon_{\text{fs}} \frac{bl_i{}^2}{6} \end{aligned} \tag{41}$$

Then we get the following factors, 1) $l_i (1 < i < n)$, the optimal length of layer C_i; and 2) $d_i (1 < i < n)$, the optimal transmission distance of layer C_i.

$$\begin{cases} l_i = \frac{p_{i-1}}{\sqrt[3]{\sqrt{(q_{i-1}^2 - p_{i-1}^3)} - q_{i-1}}} + \sqrt[3]{\sqrt{(q_{i-1}^2 - p_{i-1}^3)} - q_{i-1}} - \frac{\alpha_{i-1}}{6\gamma} \\ d_i = \frac{l_{i-1} + l_i}{2} \\ p_{i-1} = \frac{\alpha_{i-1}^2}{36\gamma^2} + \frac{\delta_{i-1}}{6\gamma} \\ q_{i-1} = \frac{\varepsilon_{i-1}}{4\gamma} + \frac{\alpha_{i-1}^3}{216\gamma^3} + \frac{\alpha_{i-1}\delta_{i-1}}{24\gamma^2} \\ \alpha_{i-1} = 3b\varepsilon_{\text{fs}} L - 3b\varepsilon_{\text{fs}} \sum_{x=1}^{i-1} l_x \\ \gamma = b\beta\varepsilon_{\text{fs}} \\ \varepsilon_{i-1} = -3b\varepsilon_{\text{fs}} l_{i-1}^2 \sum_{x=1}^{i-1} l_x + 3Lb\varepsilon_{\text{fs}} l_{i-1}^2 \\ \qquad - 24be_{\text{elec}} \sum_{x=1}^{i-1} l_x + 24be_{\text{elec}} \\ \delta_{i-1} = 6b\varepsilon_{\text{fs}} l_{i-1} \sum_{x=1}^{i-1} l_x - 6b\varepsilon_{\text{fs}} L l_{i-1} + 12be_{\text{elec}} \\ \qquad + 12\beta\bar{E}_{1\min} - 24be_{\text{elec}}\beta \\ \bar{E}_{1\min} = \frac{2Lb}{\beta l_1} e_{\text{elec}} + 2\left(1 + \frac{1}{\beta}\right) be_{\text{elec}} + \frac{\varepsilon_{\text{fs}} Lb}{\beta} l_1 \\ \qquad + \left(\frac{1}{6} - \frac{1}{2\beta}\right) \varepsilon_{\text{fs}} b l_1{}^2 \\ l_1 = \omega + \frac{L^2}{16\omega\beta^2} - \frac{L}{4\beta} \\ \omega = \sqrt[3]{\sqrt{u - \left(\frac{L}{4\beta}\right)^6} - u} \\ u = \left[\left(\frac{L}{4\beta}\right)^3 - \frac{3L\left(2e_{\text{elec}} + \varepsilon_{\text{fs}} l_0^2\right)}{2\beta\varepsilon_{\text{fs}}}\right]^2 \end{cases} \tag{42}$$

3) CASE 3: THE LAST LAYER ($i = n$)

With the increase of i in Eq. (42), there will exist the following two situations.

Situation A: According to Eq. (40) and Eq. (42), the lengths of layer $C_1, C_2, \cdots, C_i$ just satisfy $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x = L$.

In this situation, the optimal length of layer C_n and the optimal transmission distance of layer C_n can still be obtained by Eq. (42).

Situation B: According to Eq. (40) and Eq. (42), the lengths of layer $C_1, C_2, \cdots, C_i$ just satisfy $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x > L$.

In this situation, we get the following optimal length of layer C_n and the optimal transmission distance of layer C_n.

$$\begin{cases} l_n = L - \sum_{x=1}^{i-1} l_x \\ d_n = \frac{l_{n-1} + l_n}{2} \end{cases} \tag{43}$$

This length of layer C_n can be demonstrated in Fig. 5 as an example.

In summary, according to Eq. (39), Eq. (42) and Eq. (43), the optimal length and transmission distance of every layer have been obtained.

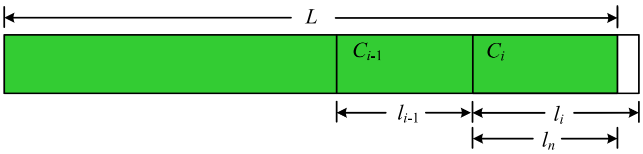

FIGURE 5. The length of layer C_n.

E. THE TOTAL NUMBER OF LAYERS

According to Eq. (42) and Eq. (43), the total number of layers of the network can be achieved as

$$
\begin{cases}
n = i \\
\text{s.t.} \sum_{x=1}^{i-1} l_x < L \\
\sum_{x=1}^{i} l_x \geq L \\
l_i = \frac{p_{i-1}}{\sqrt[3]{\sqrt{\left(q_{i-1}^2 - p_{i-1}^3\right)} - q_{i-1}}} + \sqrt[3]{\sqrt{\left(q_{i-1}^2 - p_{i-1}^3\right)} - q_{i-1}} - \frac{\alpha_{i-1}}{6\gamma} \\
d_i = \frac{l_{i-1}+l_i}{2} \\
p_{i-1} = \frac{\alpha_{i-1}^2}{36\gamma^2} + \frac{\delta_{i-1}}{6\gamma} \\
q_{i-1} = \frac{\varepsilon_{i-1}}{4\gamma} + \frac{\alpha_{i-1}^3}{216\gamma^3} + \frac{\alpha_{i-1}\delta_{i-1}}{24\gamma^2} \\
\alpha_{i-1} = 3b\varepsilon_{\text{fs}}L - 3b\varepsilon_{\text{fs}} \sum_{x=1}^{i-1} l_x \\
\gamma = b\beta\varepsilon_{\text{fs}} \\
\varepsilon_{i-1} = -3b\varepsilon_{\text{fs}} l_{i-1}^2 \sum_{x=1}^{i-1} l_x + 3Lb\varepsilon_{\text{fs}} l_{i-1}^2 \\
\quad - 24be_{\text{elec}} \sum_{x=1}^{i-1} l_x + 24be_{\text{elec}} \\
\delta_{i-1} = 6b\varepsilon_{\text{fs}} l_{i-1} \sum_{x=1}^{i-1} l_x - 6b\varepsilon_{\text{fs}} L l_{i-1} + 12be_{\text{elec}} \\
\quad + 12\beta \bar{E}_{1\min} - 24be_{\text{elec}}\beta \\
\bar{E}_{1\min} = \frac{2Lb}{\beta l_1} e_{\text{elec}} + 2\left(1+\frac{1}{\beta}\right) be_{\text{elec}} + \frac{\varepsilon_{\text{fs}} Lb}{\beta} l_1 \\
\quad + \left(\frac{1}{6} - \frac{1}{2\beta}\right) \varepsilon_{\text{fs}} b {l_1}^2 \\
l_1 = \omega + \frac{L^2}{16\omega\beta^2} - \frac{L}{4\beta} \\
\omega = \sqrt[3]{\sqrt{u - \left(\frac{L}{4\beta}\right)^6} - u} \\
u = \left[\left(\frac{L}{4\beta}\right)^3 - \frac{3L\left(2e_{\text{elec}} + \varepsilon_{\text{fs}} l_0^2\right)}{2\beta\varepsilon_{\text{fs}}}\right]^2
\end{cases}
\tag{44}
$$

It can be revealed from Eq. (44) that the total number of layers of the network is determined by three factors: the length of the network, the data generation speed, and the data fuse rate.

F. POSSIBILITY ANALYSIS OF BALANCED ENERGY DEPLETION

1) ANALYSIS OF SITUATION A

As mentioned above, in *Situation A*, the lengths of layer $C_1, C_2, \cdots, C_i$ just satisfy $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x = L$. Both the optimal length of layer C_n and the optimal transmission distance of this layer are obtained by Eq. (42), which is based on the energy balance principle of Eq. (41). In other words, the premise of Eq. (42) is that the AECIN of any other layer be equal to the minimum one of layer C_1. Therefore, balanced energy depletion of individual nodes can be achievable in *Situation A*.

2) ANALYSIS OF SITUATION B

As mentioned above, in *Situation B*, the lengths of layer $C_1, C_2, \cdots, C_i$ just satisfy $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x > L$, and both the optimal length of layer C_n and the optimal transmission distance of this layer are obtained by Eq. (43).

It is apparent from Fig. 5 that the length l_n obtained by Eq. (43) is less than that obtained by Eq. (42). Likewise, the transmission distance d_n obtained by Eq. (43) is less than that obtained by Eq. (42).

In the layer C_n, energy depletion only contains transmitting rather than receiving. According to Eq. (1), energy depletion is proportion to data to be delivered. In the layer C_n, both the nodes and the data to be delivered are proportion to the length l_n. So, with the decrease of the length l_n, the data to be delivered doesn't affect the AECIN of this layer, but with the decrease of the transmission distance d_n, the AECIN of this layer begins to diminish. In other words, the AECIN of this layer is less than that of other layers. Therefore, balanced energy depletion of individual nodes cannot be achieved in *Situation B*. Even so, the subbalanced energy depletion can be attained by Eq. (43).

3) ANALYSIS OF BALANCED/SUBBALANCED ENERGY DEPLETION

As analyzed above, if we need completely balanced energy depletion, *Situation A* must be met, namely the lengths of layer $C_1, C_2, \cdots, C_i$ must satisfy the specific condition $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x = L$. Clearly, this is a rare case, in which balanced energy depletion can be obtained in the strip-based WSNs.

In general,*Situation B* exists, namely the lengths of layer $C_1, C_2, \cdots, C_i$ satisfy $\sum_{x=1}^{i-1} l_x < L$ and $\sum_{x=1}^{i} l_x > L$. Apparently, in most cases, i.e. in *Situation B*, only the subbalanced energy depletion can be attained in the strip-based WSNs.

V. PERFORMANCE EVALUATION

A. BASIC DESCRIPTION

In this section, the performance of ADTS is evaluated through extensive simulations, which are conducted in different sizes of networks. To demonstrate the efficiency and advantages of ADTS in terms of load balance level and network lifetime, ADTS is compared with three conventional transmission methods: 1) a direct transmission manner named DT [15]; 2) a multihop transmission scheme named EEGR [15]; and 3) a hybrid transmission method named EBDG [15]. All the parameters of the experiment are listed in Table 1.

TABLE 1. The parameters of the evaluated WSNs.

Parameter	Meaning	Value
H	height of the network	10m
L	length of the network	400m ~1000m
ρ	node density	1 node/m^2
$1/\beta$	ratio of data fusion	1/50
E_0	initial energy of each node	5J
b	speed of data fusion	500bits/round

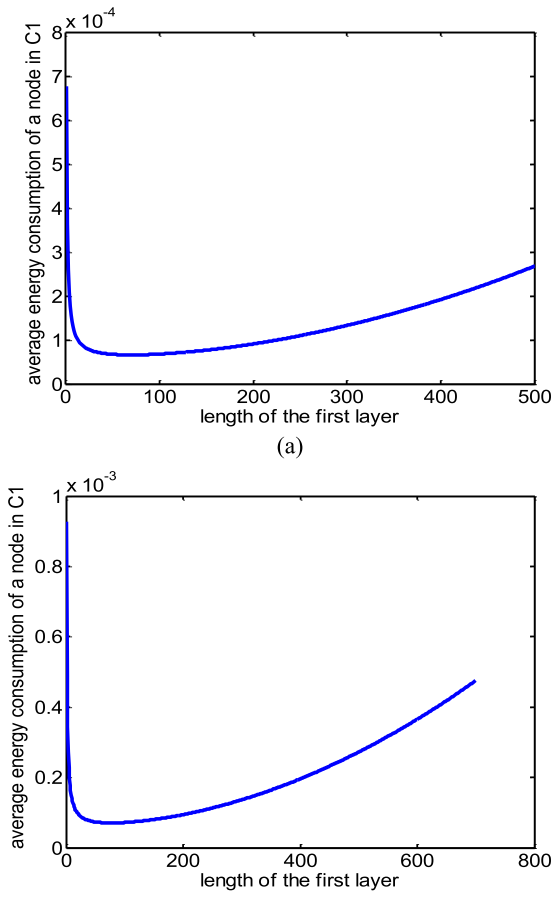

FIGURE 6. Energy consumption of the first layer. (a) L = 500m. (b) L = 700m.

B. IMPACT OF THE LENGTH OF THE FIRST LAYER ON THE ENERGY CONSUMPTION

Fig. 6 demonstrates the impact of the length of the first layer on energy consumption. It can be seen from the figure that, if the length of the first layer approximates to zero, the energy consumption rises sharply, due to the reception of too much data which suffers from energy dissipation. Moreover, if the length of the first layer grows very large, the energy consumption also increases, on account of the large transmission distance which also leads to large energy expenditure.

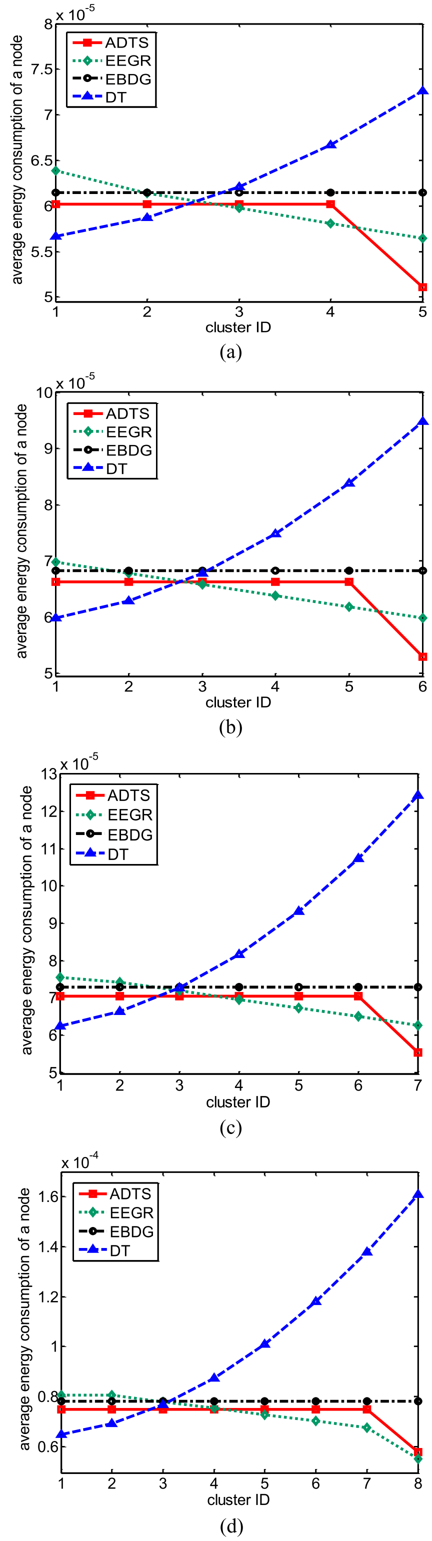

FIGURE 7. Energy consumption of different layers. (a) L = 400m. (b) L = 600m. (c) L = 800m. (d) L = 1000m.

C. COMPARISON OF THE ENERGY BALANCE LEVEL

The energy balance level is tested in Fig. 7, which demonstrates the AECIN of different layers. The network lifetime is determined by the maximum AECIN of different layers.

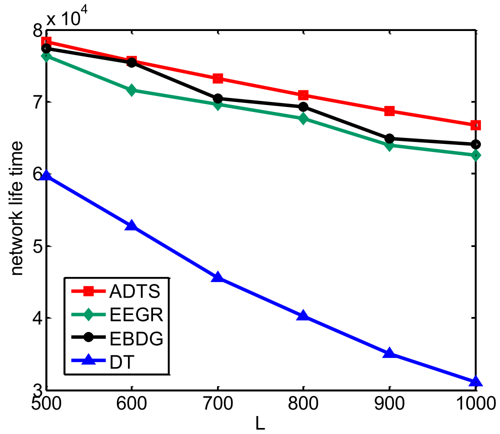

FIGURE 8. Network lifetime of different network sizes.

It can be shown from Fig. 7, the AECIN of DT rises rapidly with the increase of the layer number, due to the fact that the energy depletion is related to the square of the distance to the sink in single-hop communications. There is a large difference in the AECIN of DT among different layers, i.e. the load balance level of DT is poor. Furthermore, although the load balance level of EBDG is the best in Fig. 7, its AECIN is larger than that of ADTS. Moreover, the maximum AECIN of ADTS is smaller than that of any other one. Despite the AECIN of ADTS of the last layer is obviously less than that of others, this doesn't affect the network lifespan.

D. COMPARISON OF THE NETWORK LIFETIME

Network lifetime has different definitions and measuring methods, such as the first node to die, the number of alive nodes, the fraction of alive nodes, the time until the network fails to construct a backbone, and etc. [32]. Here, the network lifetime is defined as the time which elapses till the first node in the network uses up its energy, which is similar to that in [33].

Fig. 8 shows the maximum transmission round before the death of the network for different algorithms. It can be revealed from this figure that the values of all algorithms decline with the rising of the network size. The reason is that, with the increase of the network size, more data needs to be delivered throughout the network and this increases the load of nodes, especially those near the sink. The maximum transmission round of DT is the smallest one all the time in the figure, on account of the long-distance direct communications. ADTS has the largest value of the maximum transmission round all the time in this figure. This is because of the accurate lengths and the optimal transmission distances of different regions.

VI. CONCLUSION

This paper makes a first attempt to solve the transmission problem for strip-based WSNs. We achieve the most precise layer lengths so far and the optimal transmission distances of different regions in such a network. This provides significant design references for data transmission of strip-based WSNs. Extensive simulations are used to validate the effectiveness and advantages of our findings.

Future research of this work can be done in the field of transmission design assisted by super nodes. Considering the powerful capabilities of computations and communications of super nodes, applying such nodes to strip-based WSNs is an interesting task.

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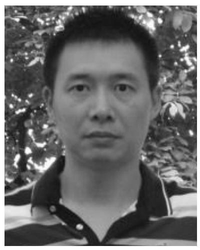

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