Research Article

A Type of Node Deployment Strategy Based on Variable Acceleration Motion for Wireless Sensor Networks

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For the purpose of balancing node energy consumption in Wireless Sensor Networks and in the premise of considering network coverage, a kind of node broadcasting scheme at fixed intervals under variational acceleration straight-line movement model is proposed in this paper. Simulation results illustrate that the approach proposed in this paper has a superior performance on balance of energy consumption compared to IEA method and uniform broadcasting as well as random broadcasting methods. And the energy saving effect is close to that of the theoretical deployment model of data fusion and nondata fusion.

1. Introduction

Energy balance is a key metric impacting the performance of Wireless Sensor Networks (WSNs) [1, 2]. One of the most efficient methods to achieve energy balance is to optimize the deployment and configuration of WSNs [3–9]. However, it is well known that designing a Wireless Sensor Network is a difficult task, especially the sensor node deployment which has an impact on the coverage, the network connectivity, and the network lifetime as well as the cost of the WSNs [10].

For practical applications, deterministic deployments can be time-consuming and error-prone, since they have the utmost challenge of guaranteeing connectivity and proper area coverage upon deployment. The deployment problem has been the topic of much research work. However, the majority of the work focuses on theoretical lab-appropriate approaches for carefully positioning nodes to meet research requirements [11–13].

On the other hand, currently, random broadcasting and uniform clustering methods are adopted in most multihop WSNs [14]. By communicating among nodes and sleep scheduling, it could save more energy to extend network lifetime. However, it is difficult to achieve an energy balance [15–17]. In the multihop communication network of WSNs, the closer to the base station, the energy of the node will be consumed faster. If a large number of nodes nearby the base station are dead, there will be an isolated subnet with the base station, and then the data will not be able to reach the base station anymore. This is also known as hot spot problem of the multihop network [18]. Therefore, how to design a flexible deployment and broadcasting model for nodes is a chief problem in WSNs [3].

2. Related Works

There is considerable literature addressing various aspects of energy balancing deployment. Fan et al. [19] propose a type of deployment strategy with relay nodes to ensure energy balance. By computing the most proper transmission distance, several relay nodes are set between source nodes and the base station to achieve balance between the energy consumption of sensor nodes and relaying nodes. However, this strategy takes a considerable cost in time and cannot be applied in large-scale networks; Fei [20] proposes a grid based network deployment algorithm. In this algorithm, each grid defines an inner node, which has the least distance from the grid center as its cluster. Besides, it utilizes the gateway to gather the information in a cluster then deliver it to the nearest cluster head. This deployment strategy owns
the advantages for the convenience of information management and data fusion. But it should be noted that energy unbalance is also a key problem in this network. In addition, Liu [21] proposes a new method of deployment using ant colony iteration in grid models which reaches the goal of coverage with minimum nodes.

Besides optimizing deployment schemes, heterogeneous initial energy allocation and modulation modes are proposed by some literatures as well to achieve energy balance. Ren et al. [22] provide a method called IEA. In this method, initial energy of each node is allocated according to its distance from the base station. Then, the initial energy difference between neighboring nodes is simplified as a constant value. However, the error in IEA cannot be neglected, and in real networks it is usually impossible to prior allocate initial energy. Soltan et al. [23] propose another method to achieve energy balance. In a circular network, they choose noncoherent BFSK with low complexity and high SNR for the nodes near the base station, and coherent BPSK with high complexity and relative low SNR for the nodes far from the base station. But, like IEA, this method cannot achieve self-adaptation in a varied network. In addition, heterogeneous modulation causes low transmission efficiency.

By computing network lifetime after deployment, Hou et al. [24] adjust the location of relay nodes to maximize the network lifetime. But this method takes a heavy cost for the process of iteration and cannot adapt itself with varied networks. Ren et al. [25] propose a distance-based energy efficient placement in circular networks. Though coverage has been taken into consideration in this deployment, it fails to analyze the energy consumption on the condition of data fusion. In addition, [26–28] provide a similar method in which circular networks are to be divided into several rings with different radii. By utilizing this method to figure out the minimum value of the objective function, it is easy to get the optimum radius for each ring. However, it also ignores the network coverage problem.

Based on the above researches and taking real physical environment into account, this paper proposes a new broadcasting method, in which the thrower is undergoing a straight-line motion with varied acceleration and broadcasts at a fixed rate. Section 3 of this paper provides a detailed realization process, and the simulation of this method is shown in Section 4. The conclusion is provided in Section 5.

### 3. Method Description

#### 3.1. Energy Balance Oriented Theoretical Deployment Model of WSNs

The major properties of WSNs are random broadcasting and multihop transmission [3–6]. As a result, it is wise to firstly analyze the energy balance of a linear multihop network model. As Figure 1 shows, a network has $N$ nodes: $S_1, S_2, \ldots, S_N$ and a base station $B$. $S_1$ is the source and $B$ is the destination node. Node $S_k$ is the forerunner of node $S_{k+1}$ which is the successor of $S_k$. The hop distance between $S_k$ and $S_{k+1}$ is $d_k$. $P_i$ ($i = 1, 2, \ldots, N$) is the size of packet needed to be gathered and delivered by node $S_i$ ($i = 1, 2, \ldots, N$). Without the consideration of data fusion, except the first node $S_1$, every node will receive the data package from its forerunner, combine them with its own data, then deliver to its successor until reaching the base station. According to [15], the following equation is valid:

$$
E_k = m [(k - 1) E_{\text{elec}} + k E_{\text{elec}} + k E_{\text{amp}} r_k^2],
$$

$$
E_{k+1} = m [k E_{\text{elec}} + (k + 1) E_{\text{elec}} + (k + 1) E_{\text{amp}} r_{k+1}^2],
$$

where $E_k$ and $E_{k+1}$ are the energy consumption during a single-time data transmission by node $S_k$ and $S_{k+1}$, respectively. $m$ is defined as number of bits of single-time data gathered by one node. $E_{\text{elec}}$ is the unit energy consumption of a transceiver, while $E_{\text{amp}}$ is the unit energy consumption of an amplifier. Moreover, it is generally recognized that the energy of sink node is sufficient. As a result, to achieve energy balance, $E_k$ should be equal to $E_{k+1}$ ($k = 1, 2, \ldots, N - 1$), which is shown as the following:

$$
(k - 1) (k - 1) E_{\text{elec}} + k E_{\text{elec}} + k E_{\text{amp}} r_k^2 = k E_{\text{elec}} + (k + 1) E_{\text{elec}} + (k + 1) E_{\text{amp}} r_{k+1}^2.
$$

Based on this equation, the relation of different hop distances in this linear structure should meet

$$
d_{k+1} = \sqrt{\frac{k d_k^2 + 2E_{\text{elec}}}{k + 1 E_{\text{amp}}}}.
$$

It is obvious to find that $d_{k+1}$ is always smaller than $d_k$, but their difference is approaching zero with the increase of $k$.

This linear model is similar to the models in literature [26–28] and can be generalized into circular networks, as Figure 2 shows. The network region is made up of a solid circle with radius $L$ and the base station is located on the center of the circle. So, several multihop transmission models of the linear structures compose an energy balancing circular network model. The hop distance of every node in the linear structure should meet

$$
\sum_{i=1}^{N} d_i = L.
$$

From Figure 2, it should be noted that nodes in the network will form several concentric circles with different radii, and the difference between radii is not uniform (as the dotted lines in Figure 2 show). It is also easy to find that given the network size, the angle of two neighboring linear structures (as angle $\theta$ in Figure 2) determines the number of nodes required to be deployed as well as the network coverage.
3.2. Deployment Model Based on Variable Acceleration Straight-Line Movement. Though energy balance can be achieved in both the linear deployment model and the concentric circular deployment model, it is difficult to locate nodes accurately. As a result, based on (3) which describes the relation between neighboring hop distances, a new deployment strategy is proposed here to simulate and substitute for the energy balance oriented theoretical deployment model. In this strategy, the thrower is undergoing a straight-line motion with a decreasing acceleration. Its motion starts with the initial speed $v_1$ and an initial acceleration $a_0$, which decreases at a rate $r$. Let $a(t)$, $v(t)$, and $S(t)$ denote the instantaneous acceleration and instantaneous velocity and displacement; then we know

$$a(t) = a_0 - rt,$$

$$v(t) = v_1 - \int_0^t a(t) \, dt = v_1 - a_0 t + \frac{1}{2}rt^2,$$

$$S(t) = \int_0^t v(t) \, dt = v_1 t - \frac{1}{2}a_0 t^2 + \frac{1}{6}rt^3. \tag{5}$$

Let $P$ deploy a node at its instantaneous position with a fixed time $T$ interval. According to the rule of straight-line motion with variable acceleration, the distance between two neighboring nodes will be smaller, which is similar to the energy balance oriented deployment scheme demonstrated in Section 3.1. Figure 3 points out the deployment positions $S_1, S_2, \ldots, S_N$ ($v_1, v_2, \ldots, v_N$ are the instantaneous velocity of $P$ at this deployment position), where the nodes should be deployed. So, we get

$$d'_1 = v_1T - \frac{1}{2}a_0 T^2 + \frac{1}{6}RT^3,$$

$$d'_2 = v_1T - \frac{3}{2}a_0 T^2 + \frac{7}{6}RT^3,$$

$$d'_3 = v_1T - \frac{5}{2}a_0 T^2 + \frac{19}{6}RT^3. \tag{6}$$

By mathematical induction

$$d'_k = v_1T - \frac{1}{2} (2k - 1) a_0 T^2 + \frac{1}{6} (3k^2 - 3k + 1) RT^3,$$

$$d'_{k+1} = v_1T - \frac{1}{2} (2k + 1) a_0 T^2 + \frac{1}{6} (3k^2 + 3k + 1) RT^3. \tag{7}$$

Then we get

$$d'_{k+1} = d'_k - a_0 T^2 + krT^3. \tag{8}$$

Equation (3) shows that we should ensure $d_k$ is larger than $d'_{k+1}$ for all $k$, in order to achieve an energy balance. So, (8) can be transformed to

$$krT^3 - a_0 T^2 < 0, \tag{9}$$

so

$$k < \frac{a_0}{rt}. \tag{10}$$

Equation (8) illustrates, similar to (3), with the increase of $k$, $d'_{k+1}$ is approaching $d_k$ indefinitely, proving that the tendencies of these two equations are the same. So, it is feasible to adopt straight-line motion with variable acceleration to simulate energy balance oriented deployment scheme in WSNs.

However, in most practical cases, broadcasting by air is used as a major deployment way. As a result, it needs to take some improvement, as shown in Figure 4. Similar to Figure 3, $S_1, S_2, \ldots, S_N$ are broadcasting points for an aircraft undergoing a straight-line motion with a decreasing acceleration, while $S'_1, S'_2, \ldots, S'_N$ are the points where the nodes have landed. Let $h$ denote the height of the aircraft, and $T$ denote the broadcasting interval. It is obvious that, after being broadcasted, the nodes undergo free fall motion in vertical direction and uniform motion with velocity $v_1, v_2, \ldots, v_N$ in horizontal direction.

From Figure 4, it can be inferred that the relation between $d'_k$, the distance between two neighboring broadcasted points, and $d''_k$, the distance between two neighboring real landed points, is shown as

$$d''_k = d'_k - V ((k - 1) T) \times \sqrt{\frac{2h}{g}} + V (kT) \times \sqrt{\frac{2h}{g}}, \tag{11}$$
Similarly, the distance from the thrower to the kth node after T time unit is given by:

\[ d''_{k+1} = d''_{k} - V(T) \times \sqrt{\frac{2h}{g}} + V((k+1)T) \times \sqrt{\frac{2h}{g}} \tag{12} \]

So, from (8), (11), and (12), it can be inferred that

\[ d''_{k+1} = d''_{k} - a_0 T^2 + kr T^3 + rT^2 \sqrt{\frac{2h}{g}} \tag{13} \]

\[ k < \frac{1}{T} \left( \frac{a_0}{r} - \sqrt{\frac{2h}{g}} \right) \tag{14} \]

From (13), if the thrower undergoes a straight-line motion with a variable acceleration and is broadcasting nodes with a fixed time interval T, the real linear structures formed by landed nodes in network region are similar to the structure under the energy balance oriented linear network deployment. In addition, on the condition of air broadcasting, the difference between neighboring hop distances is much smaller than that in other deployments.

From what has been discussed above, we assume that the thrower undergoes a decelerated motion with a decreasing acceleration first and then an accelerated motion with an increasing acceleration along a diameter of the network region. Thus, the deployment of nodes in the linear structure along that diameter can be accomplished.

The initial velocity is \( v_1 \), initial acceleration is \( a_0 \), and its decreasing rate is \( r \). The broadcasting interval is also \( T \). Once the thrower reaches the base station located at the center of the network, its motion changes to be an accelerated motion with an increasing acceleration. The new initial velocity is \( v_{N+1} \), new initial acceleration is \( a(N \times T) \), and its increasing rate is \( r \). This process is shown in Figure 5.

From Figure 2, in order to ensure energy balancing, the location of deployed nodes will form several concentric circles and the difference of radii of neighboring circulars obeys (3). Similarly, after several air broadcastings, the deployed nodes will form several concentric circles, whose radius are different and their difference is not uniform. The difference between radii of neighboring circles meets (13).

3.3. Coverage Guaranteed Air Broadcasting Deployment Scheme. By the model of air broadcasting under variable acceleration straight-line movement, a linear network can be well deployed. Then, how many times should a thrower move and broadcast to guarantee to cover the whole network region? The key is up to the angle \( \theta \) shown in Figure 2. From the discussion above, \( \theta \) determines the number of nodes which are needed to be deployed. In this sense, \( \theta \) relates with not only the whole energy consumption, but also the network coverage rate.

In [25], in a concentric circle deployed network, the author finds that the whole circular region could be ensured covered if and only if the circumference composed of the outermost nodes satisfies the requirement of network coverage rate. Assume node sensing radius is \( R \). Let \( d_1 = R \) and make sure the sensing circles of two outermost nodes, which are deployed in neighboring broadcastings, are tangent. Figure 6 proves that when the broadcasting angle is \( \theta \), except in several small regions at the fringe of the network (demonstrated as the shaded parts in Figure 6), a casual point in the network is covered by at least one node. Consider

\[ \sin \theta = \frac{2R \sqrt{\left( \sum_{i=1}^{N} d''_i \right)^2 - R^2}}{\left( \sum_{i=1}^{N} d''_i \right)^2}, \tag{15} \]

\[ R + \sum_{i=1}^{N} d''_i = L. \]

So

\[ \theta = \arcsin \frac{2R \sqrt{\left( \sum_{i=1}^{N} d''_i \right)^2 - R^2}}{\left( \sum_{i=1}^{N} d''_i \right)^2}. \tag{16} \]

To the whole network, the number of times of straight-line broadcastings is \( \lceil \pi/\theta \rceil \), while the number of deployed nodes is \( 2N \lceil \pi/\theta \rceil \). In addition, \( v_1 \) should meet the following equation:

\[ v_1 \times \sqrt{\frac{2h}{g}} = R. \tag{17} \]
3.4. EnergyBalancingDeploymentSchemewithDataFusion.
Inapreviousenergybalanceorienteddeploymentstrategy
andfixedintervalairbroadcastingwithavariableaccelera-
tion motion, it is assumed that the schemes ignore the data
fusion. However, in real WSNs, as the sensing regions overlap
and the redundancy cannot be neglected, it is necessary to do
data fusion in relaying nodes.

Here, we analyze the deployment method for linear
structuresasFigure7shows.Giventhatthedatafusionratio
transmitted data are

\[ m \sum_{j=1}^{k-1} \eta^j \]

and the redundancy cannot be neglected, it is necessary to do
data fusion in relaying nodes.

As \( \eta \) is a number less than one, \( \eta^{k} \) is approaching zero. So,
\( E_k \) can be expressed approximately as

\[
E_k \approx \left( m \sum_{j=1}^{k-2} \eta^j + m \sum_{j=1}^{k-1} \eta^j \right) E_{elec} \\
+ \epsilon_{amp} d_k^2 m \sum_{j=1}^{k-1} \eta^j + c m \sum_{j=0}^{k-2} \eta^j.
\]  

(20)

In the same way, we get

\[
E_{k+1} \approx \left( m \sum_{j=1}^{k-1} \eta^j + m \sum_{j=1}^{k} \eta^j \right) E_{elec} \\
+ \epsilon_{amp} d_{k+1}^2 m \sum_{j=1}^{k} \eta^j + c m \sum_{j=0}^{k-1} \eta^j,
\]  

(21)

then we can infer

\[
d_{k+1} = \sqrt{\frac{1 - \eta^{k-1}}{1 - \eta^k}} d_k^2 - \left( \frac{(\eta^{k+1} + \eta^k) E_{elec} + \eta^{k-1} \epsilon}{\epsilon_{amp} \sum_{j=1}^{k} \eta^j} \right),
\]  

(22)

for \((1-\eta^{k-1})/(1-\eta^k)\) is always less than one and is approaching
one while the value of \((((\eta^{k+1} + \eta^k) E_{elec} + \eta^{k-1} \epsilon)/\epsilon_{amp} \sum_{j=1}^{k} \eta^j)\)
is approaching zero with the increase of \(k\); \(d_{k+1}\) is always
smaller than \(d_k\) and will approach \(d_k\) with the increase of \(k\) as
well. It is similar to the energy balancing deployment and air
broadcasting method with a variable acceleration movement,
which is not considering data fusion. Therefore, the new
strategy in this paper can be simulated as the deployment with
data fusion.

4. Simulation Results

4.1. Simulation Environment. To test the properties of the
deployment of broadcasting nodes with a variable acceleration
movement, the simulation is operated under Omnet++3.2 and Matlab7.0.
The values of the deployment
under test are deployment effect, network residual energy,
and its standard deviation. Then we compare the result of the
test with that of IEA method and the uniform and random
broadcasting methods. Set the network as a circle with 900
meters radius and the major parameters are shown in Table 1.

4.2. SimulationResult. Figures8and9showthesimulation
results of broadcasting with variable acceleration straight-
line movement and energy balancing deployment without
data fusion. From the simulation, the effects of the two
deployments are nearly the same, and the density of nodes
increases as the distance from the base station decreases. In
the method proposed in this paper, the hop distance between
two nodes far away from the base station is a little less than
the hop distance in energy balancing deployment model, while
the density of nodes near the base station is a little less than
that in energy balancing deployment model.
Table 1: The major parameters of simulation.

| Simulation parameters                  | Symbol | Value | Unit   |
|----------------------------------------|--------|-------|--------|
| Network size                           | $S$    | $900^\circ \times \pi$ | m$^2$ |
| Maximum node sensing radius            | $R$    | 100   | m      |
| Node initial energy                    | $E_{\text{init}}$ | 10    | J      |
| Height of broadcasting                 | $h$    | 125   | m      |
| Initial velocity of thrower            | $v_i$  | 20    | m/s    |
| Initial acceleration of thrower        | $a_0$  | 0.3   | m/s$^2$|
| Acceleration changing rate             | $r$    | 0.003 | m/s$^3$|
| Unit energy consumption of transceiver | $E_{\text{elec}}$ | 50    | nJ/bit |
| Unit energy consumption of amplifier    | $e_{\text{amp}}$ | 100   | pJ/bit/m$^2$ |
| Broadcasting interval                  | $T$    | 12    | s      |

Figures 8 and 11 demonstrate a comparison between our method and the two energy balancing ensured theoretical deployment models. It can be concluded that whether or not to execute data fusion, our method shows no difference in residual energy and its standard derivation. So, it is proved that the deployment of air broadcasting with variable acceleration movement is able to, in some sense, achieve an energy balance. In addition, the deployment on the condition of data fusion should pay attention to the energy balance for data transmission and fusion; its property of energy balancing is a little worse compared with the condition of not adopting data fusion operation, and their property difference will be enhanced as the network operates.

To testify the effects of the variation of parameters in the simulation, we set $T$ to 10 s, 12 s, and 14 s, respectively, and then observe and compare the effect of the deployment and energy consumption. The comparison is shown in Figures 14 and 15.

From the figures, we note that a too large or short interval $T$ will make the effect of deployment depart from the promised prospect, causing an unbalance of energy consumption. If $T$ is set to a feasible value, after an air broadcasting with a variable acceleration movement, the hop distance between neighboring nodes in the network will correspond with the energy balancing deployment model, showing a good energy balance.

Figures 16 and 17 show the energy balancing analysis on the condition of different data fusion ratio. If the ratio of data fusion is low ($\eta = 0.9$), the data transmission pressure of nodes is not significantly decreased. In such circumstance, the effect of network deployment is like that of the energy balance oriented deployment which makes a good energy balance. However, if the ratio of data fusion is relatively high ($\eta = 0.7$), the quantity of transmission data is significantly decreased, especially for the nodes near the base station. In this circumstance, the standard derivation of residual energy comes to increase but, however, is still far less than the derivation in uniform and random broadcasting.

Figures 10 and 11 show the average residual energy of nodes and their standard deviation. As the broadcasting result of our method is similar to the result of energy balancing linear deployment model, the residual energy will reach its maximum and its standard derivation will reach its minimum, which means it has the best energy balance. In a nascent condition of the network, IEA method can achieve a good energy balance as well, and it is nearly the same with the air broadcasting with variable acceleration movement. However, its initial energy setting is just based on the distance from that node to the base station, and the difference of initial energy of neighboring nodes is constant, so after the network operates for a long time, the energy balance will be broken and the result of IEA is close to uniform broadcasting. It is also easy to find that the residual energy of a node is least and the property of energy balancing is worst under random broadcasting deployment.

It should be noted that after the network operates for 1800 turns, the standard derivations of node residual energy in uniform and random broadcasting undergo a significant decrease. It is because there appear a lot of dead nodes, and the number of living nodes reduces rapidly. Therefore, the difference of each node’s residual energy is not significant.
5. Conclusion

This paper utilizes a variable acceleration movement model to propose a broadcasting scheme to simulate the energy balance oriented deployment model. Based on the consideration of coverage rate, a practical implementation process is provided. The analysis of its simulation result proves this new deployment approaches the theoretical deployment and achieves a good energy balance.

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Figure 14: Effects of deployments with different interval.

Figure 15: Standard derivation of node residual energy of deployments with different interval.

Figure 16: Effects of different deployment with different data fusion ratio.

Figure 17: Standard derivation of node residual energy with different data fusion ratio.

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