Journal of Computers Vol. 29 No. 5, 2018, pp. 272-281
doi:10.3966/199115992018102905022

Wireless Sensor Networks Based on 3DAK Protocol

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Received 2 January 2018; Revised 7 July 2018; Accepted 7 August 2018

Abstract. In order to ensure the traffic safety of high speed train, it is necessary to deploy wireless sensor networks in viaduct, cutting and tunnel space along the railway for comprehensive environmental monitoring. However, there are few studies on low energy routing protocol for wireless sensor networks in three-dimensional space. This paper presents a 3DAK (3D advanced K-means) routing protocol based on three dimensional advanced K-means clustering algorithm, which calculates the minimum node density by constructing Reuleaux tetrahedron model to ensure the communication connectivity between nodes. We can obtain the optimal wireless sensor node density and cluster average size through simulation results. Moreover, the cluster heads are determined by combination of the residual energy and the location of nodes. Simulation results show that 3DAK routing protocol can better save energy, prolong the network lifetime and improve the survival number of nodes compared to other classical routing protocol.

Keywords: K-means clustering, Reuleaux tetrahedron, routing protocol, three-dimensional space, wireless sensor networks

1 Introduction

In order to ensure the traffic safety of high speed train, wireless sensor networks often deployed in these scenarios such as viaduct, cutting and tunnel space along the railway to realize the function of environmental monitoring. However, there are very few studies on low energy routing protocol for wireless sensor networks in three-dimensional space. The majority of studies on wireless sensor networks consider two dimensional scenarios although the actual sensor nodes are deployed in 3D space. Due to the high speed train environment monitoring requires comprehensive data, hence it's meaningful to study 3D environment of wireless sensor networks for the traffic safety of high speed train.

One of the main design goals of the networks is saving the energy of nodes that deployed in wireless sensor networks, the current studies show that the goal can be achieved through the following aspects.

In the aspect of sensor node density, reasonable node density can contribute to save network energy. It has very much studies in node density of 2D space although very few in the 3D space, even the study of the density of nodes in 3D space can make the results more accurate. In [1], it structures Reuleaux tetrahedron model by the cross of nodes' sensing range, and calculates the corresponding minimum space density. In [2], it deepens the study on the Reuleaux tetrahedron model by aiming at the k coverage problem to calculate the minimum node density.

In the aspect of clustering algorithm, clustering wireless sensor networks can contribute to reduce the energy cost. Many clustering algorithms have been proposed at present, and K-means clustering algorithm [3] is one of the well-known algorithms. Two ways of K-means clustering algorithm [4] for

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wireless sensor networks are proposed: distributed and central, and proves that the distributed is more stable than central by simulation and comparison. [5] proposed a distributed K-means clustering algorithm based on the attribute-weighted-entropy regularization technique to improve the wireless sensor networks' clustering efficiency.

Routing protocol is the basis of the sensor networks' study and core technology, an efficient routing protocol can greatly save the energy consumption of wireless sensor networks. At present, the majority of studies on routing protocol focuses on 2D domain, such as [6] presents the method of energy consumption balance of LEACH, [7] studies SEP protocol for heterogeneous wireless sensor networks. However, the study of three-dimensional wireless sensor networks has more practical significance. In [8], it provides a distributed solution for greedy routing protocol in 3D sensor networks which based on the unit tetrahedron cell (UTC) grid structure and proposed distributed algorithm in spherical boundary conditions to achieve UTC grid volume harmonic.

The purpose of this paper is saving energy of 3D wireless sensor networks, there are very few studies in 3D space using K-means or its improved algorithm to save network energy at present. Therefore, this paper proposed 3DAK routing protocol based on the improved K-means algorithm. First of all, the node density in the target area can reflect the quality of the supervision of networks, the minimum node density can be calculated through the known Reuleaux tetrahedron's volume and Reuleaux tetrahedron is structured by the cross of nodes' sensing spheres. We can get the better node density through the comparison of the MATLAB simulation results. Secondly, choosing appropriate average size of cluster is a good solution to balance energy consumption, and this paper controls the average size of cluster by the survival node number. Finally, saving node energy reflects in the proper cluster head selection method, it is necessary to consider the node residual energy and other nodes' energy consumption within clusters, therefore, this paper selects cluster head based on the principle: the node with the largest residual energy and shortest distance from the center of the cluster, the cluster head selection method can balance the energy consumption in the cluster and save energy.

The remainder of this paper is organized as follows. Section I provides the assumption and model. Section II presents detailed 3DAK routing protocol design. Section III gives the simulation results and analysis. Finally, concluding this paper and making prospect on further job.

2 Assumption and Model

In this section, we provide some useful assumptions and models for the study of 3DAK routing protocol.

2.1 Assumption

Hypothesis 1: Sensor nodes are randomly deployed in the 100m×100m×100m target area, and a proper method of deploying a small number of heterogeneous sensor nodes can effectively extend network lifetime and improve its reliability. So in our network, 10% of the nodes are advanced nodes which its initial node energy is 2E0, 90% of the nodes are ordinary nodes which initial node energy is E0.

Hypothesis 2: Nodes are able to acquire their own position and energy information after deploying, the nodes can also perceive the location and energy information of their neighbor nodes, and the nodes are stable once deployed.

Hypothesis 3: The Sink node is located in the center of the target area for effective data collection and reducing the data transmission energy consumption.

Hypothesis 4: A communication graph of a WSN is a graph G(S,L), where S is a set of sensor nodes and L is a set of communication links between nodes in the cluster and cluster heads.

Hypothesis 5: Cluster number ratio = cluster number / the number of survival nodes.

In this paper, the status of node deployment in wireless sensor network and communication graph through the simulation of the 3DAK protocol is shown in Fig. 1:

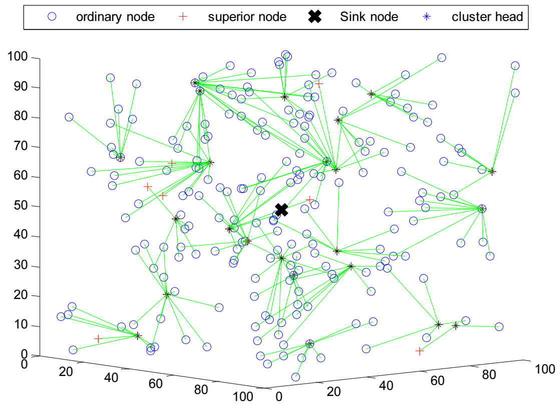

Fig. 1. Shows the mark of nodes and cluster head, and the lines in the graph represent the path from nodes to cluster heads

Hypothesis 6: The distance between any sensors S_i and S_j is the Euclidean distance $D(i,j)$.

$$D(i,j)=\sqrt{(i_x-j_x)^2+(i_y-j_y)^2+(i_z-j_z)^2}\ . \quad \textbf{(1)}$$

If $D(i,j)<R$, S_i and S_j can communicate with each other.

Hypothesis 7: The sensing and communication ranges of the node are spherical and the radius are respectively r and R, where r, $R << V^{1/3}$, $R/r \ge \sqrt{3}$. All sensor nodes are deployed in a cubic field of volume V. Moreover, we assume that the volumes of the sensing and communication spheres of sensors are negligible compared to V.

Proof: the positive view of Reuleaux tetrahedron as shown in Fig. 2.

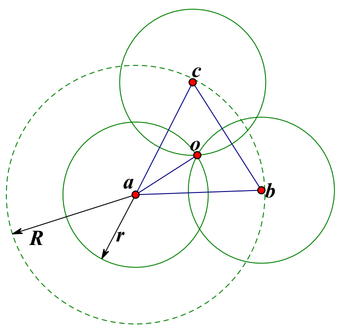

Fig. 2. The positive view of Reuleaux tetrahedron

Node *a, b, c* and their sensing circle intersect at point *o*, point *a*,*b*, and *c* construct a equilateral triangle, line *ao* equals to sensors sensing radius *r*, line *ac* equals to sensors communication radius *R*. Thus, adjacent nodes' distance is $\sqrt{3}$ times as much as sensor sensing radius, that is $R/r \ge \sqrt{3}$.

2.2 Model

2.2.1 Node Communication Model

By using the Helly theorem [9], in convex region there are at least $k \ge 4$ nodes in the 3D environment.

Helly theorem: Let Ψ be a family of convex sets in IR^n, such that for $m \ge n+1$, any members of Ψ have a nonempty intersection. Then, the intersection of all members of Ψ is nonempty.

Lemma 1 3 D convex region C covering *k* nodes, when the width of C is less than or equal to *r*.

Proof: When the width of C is larger than *r*, and we have assumed that node sensing and communication model is the spheres of radii *r* and *R*, we assume that the region C has *k* nodes, there are two nodes S_i, S_j and their distance $D(i,j)=b>r$. Let S_p is a node of the spheres center on S_i, so S_i cannot induction the event of S_j, so there are at least one node S_p can not covered S_j, so the convex C covered not k nodes. Hence the width of C is less than or equal to *r*.

By lemma 1, when the volume of the convex C reaches the maximum, the width of the C is equal to *r*.

Lemma 2 3D convex region C contains *k* nodes if its width less than or equal to the sensing radius *r* of node, 3D convex region C as shown in Fig. 3.

(a) Intersection Graph of 4 symmetrical spheres (b) Corresponding Reuleaux Tetrahedron

Fig. 3.

Theorem 1 Let *r* be the radius of sensing spheres of sensors and $k \geq 4$. The minimum sensor spatial density in 3D field is:

$$\lambda(r,k) = \frac{k}{0.422 r_o^3}. \tag{2}$$

where $r_o = r / 1.066$.

As shown in Fig. 3, the edges between the centers of these four spheres form a regular tetrahedron and the shape of intersection volume of these four spheres is known as Reuleaux tetrahedron and denoted by *RT(r)*. Unfortunately, it was proved that the Reuleaux tetrahedron does not have a constant width. Indeed, while the distance between some pairs of points on the boundary of Reuleaux tetrahedron *RT(r)* is equal to 1.066*r*, i.e., slightly larger than *r*. This implies that Reuleaux tetrahedron *RT(r)* can not be contains exactly k points given that the distance some pairs of points on the boundary of *RT(r)* is larger than *r*. Therefore, the Reuleaux tetrahedron that ensure exactly *k* sensors should have a side length equal to $r_o = r/1.066$. The volume of the Reuleaux tetrahedron $RT(r_o)$ is given by [10].

$$vol_{\max}(r_o) = ((8/3)\pi - (27/4)\cos^{-1}(1/3) + (\sqrt{2}/4)) r_o^3 \approx 0.422 r_o^3. \tag{3}$$

Therefore, $RT(r_o)$ is the maximum volume that contains exactly k sensors in convex C, where $k \geq 4$. We conclude that the maximum volume of C_k, denoted by $vol_{max}(C_k)$, is equal to $vol_{max}(C_k) = 0.422 r_o^3$. Given that $vol_{max}(C_k)$ contains k sensors, we conclude that the minimum sensors spatial density per unit volume for 3D filed is computed as:

$$\lambda(r,k) = k / vol_{\max}(C_k) = k / 0.422 r_o^3. \tag{4}$$

2.2.2 Node Energy Consumption and Survival Model

Sensor transmits and receives 1 bit data that energy consumption is computed as:

$$E_{Tx\_elec} = E_{Rx\_elec} = 1 \times E_{elec}. \tag{5}$$

Where E_{elec} is energy transmission and reception consumption per bit.

Hence, sensor transmits *k* bits data that energy consumption is computed as:

$$\begin{aligned} E_{Tx}(k,d) &= R_{Tx\_elec}(k) + R_{Tx\_amp}(k) \\ &= \begin{cases} E_{elec} \times k + \varepsilon_{fs} \times k \times d^{\beta} & d < d_0 \quad \beta = 2 \\ E_{elec} \times k + \varepsilon_{amp} \times k \times d^{\beta} & d \geq d_0 \quad \beta = 4 \end{cases} \end{aligned} \tag{6}$$

Where the transmission threshold distance denoted by d_o, the amplification factor of the long distance transmission amplifier denoted by ε_{amp}, and the amplification factor of the near distance transmission amplifier denoted by ε_{fs}.

Sensor receives *kbits* data that the energy consumption is computed as:

$$E_{Rx}(k) = R_{Tx\_elec}(k) = E_{elec} \times (k). \quad \textbf{(7)}$$

When the residual energy of the node dropped to 0, it can be regarded as death node, then the number of survival nodes = the total number of nodes - the number of dead nodes, namely STATISTICS.LIVE = *n*-dead.

3 Design of 3DAK Routing Protocol

This paper optimizes the K-means algorithm, where the cluster number is calculated by the survival node number, cluster number = survival node number ×cluster number ratio, the node would be selected as cluster head based on its residual energy is maximal and the its distance from the cluster center is shortest. The 3DAK routing protocol is proposed on the basis of the optimized K-means algorithm, and the flow chart of 3DAK protocol is shown in Fig. 4.

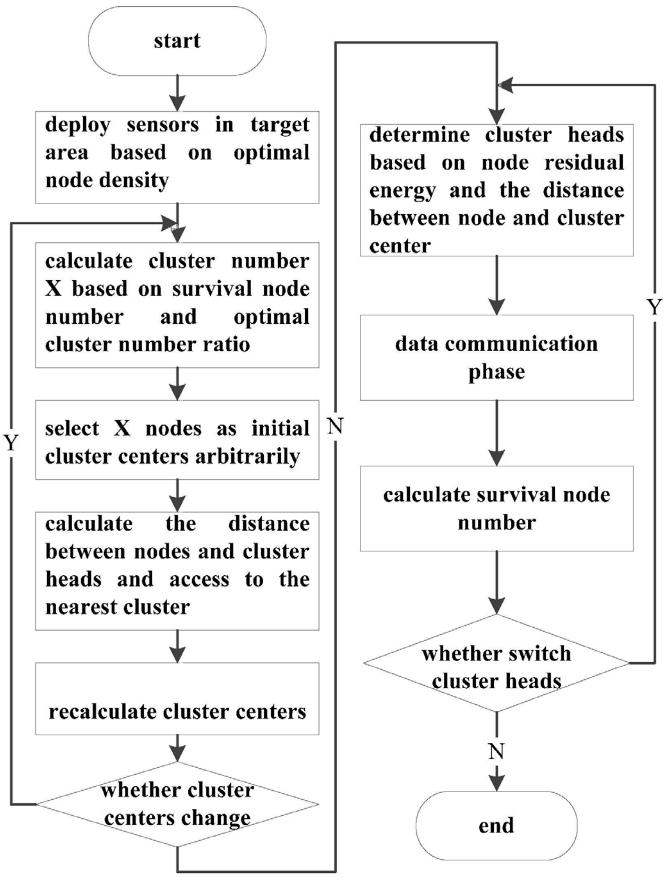

Fig. 4. Flow chart of 3DAK protocol

3DAK protocol not only has the K-means algorithm's advantages, such as simple algorithm, fast running speed, high efficiency and scalability in processing large data sets, 3DAK protocol also can balance the node energy consumption through control cluster average size to reduce the network energy consumption, and increase the number of survial nodes. The simulation results show that the 3DAK protocol has better performance than other classical protocols.

The pseudo code of the 3DAK protocol is shown in Table 1:

Table 1. 3DAK pseudo code

3DAK protocol (*S*,STATISTICS.ENERGY,STATISTICS.LIVE):
Input: $S(X_1, X_2, ..., X_n)$
Output: STATISTICS.ENERGY, STATISTICS.LIVE
Begin
for a = 0:rmax
[Dis,Col] = min (D,[],2);
dis=Dis'
col=Col'
for b = 1:size(col)
inx = find(col==b)
t=inx(b)
$S(X_a) = \max(\frac{S(t).E}{\sum_{i=1}^{i=size(inx)} S(inx(i)).E} - \frac{dis(t)}{\sum_{j=1}^{j=size(inx)} dis(inx(j))})$
$S(t).E = S(t).E - S(t).energyconsumption$
if $S(t).E \le 0$
dead = dead+1;
end
End
end
STATISTICS.LIVE = n-dead;
STATISTICS.ENERGY = $S.E$;
Note：
STATISTICS.ENERGY is network residual energy
STATISTICS.LIVE is survival node number
D is a matrix of n×*x* and presents the distance from n nodes to *x* cluster centers,
where *x* is cluster number, and *x* = n×p, p is cluster number ratio, n is totol number of nodes
Dis is the n×1 vector that presents shortest distance from n nodes to *x* cluster centers
Col is the n×1 vector that presents the cluster id which n nodes belong to
X_a is cluster head
$S.E$ is the sum of node residual energy

4 Simulation and Analysis

In this paper, we use MATLAB to simulate and analyze the performance of 3DAK protocol. In each simulation scenario, the coordinates of nodes are generated randomly. The main experiment parameters are set as follows.

Table 2. Simulation parameters

Parameter	Value
Location of Sink nodes	(50m,50m,50m)
Node quantity	180~269
Node initial energy	0.5J
Sensing radius r	40m
Cluster number ratio	0~1

According to the formula of the density of nodes, we obtain that the minimum node density is $\lambda_{\min} = \frac{4}{0.422 r_o^3}$. where $r_o = r / 1.066$. This paper analyzes their performance for getting better optimal node density under different node density through simulation, which corresponding to *k*= 4, 5, 6, namely the number of nodes are respectively 180, 225, 269, the results of network residual energy and survival node number are shown in Fig. 5 and Fig. 6.

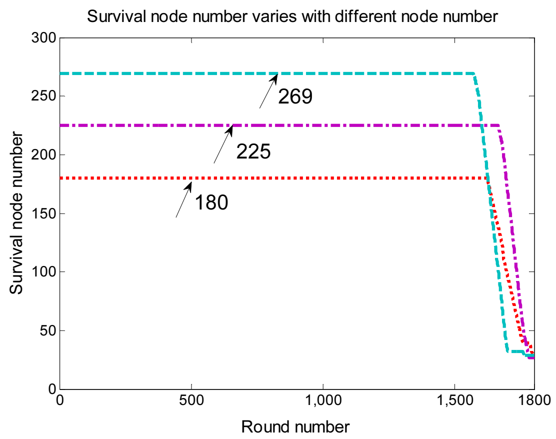

Fig. 5. Survival node number varies with different node number

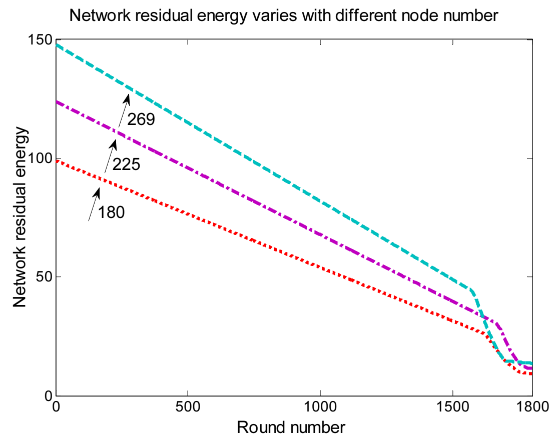

Fig. 6. Network residual energy varies with different node number

As shown in Fig. 5 and Fig. 6, we can obtain that there are subtle differences in the number of nodes 180, 225, 269 after 1800 rounds. For comparing their performance further, the results of network residual energy ratio and the survival node number ratio corresponding to the number of nodes 180, 225, 269 as shown in Table 3:

Table 3. Comparison of different node number

Node number	Total energy (J)	Residual energy (J)	Residual energy ratio (%)	Survival node number	Survival node number ratio (%)
180	99	8.9424	9.03%	21	11.67%
225	123.75	11.3556	9.18%	27	12.00%
269	147.95	13.3956	9.05%	25	9.29%

From Table 3, we can obtain the maximal network residual energy ratio and the survival node number ratio when the number of nodes is 225. When deploying few nodes in network, it indicates that the distance between nodes is large, hence the energy consumption in transmission increased, the speed of node death is increased, and result in fewer nodes and larger distance, finally lead to the network death earlier. On the contrary, when deploying a mass of nodes in network, it indicates that the average size of cluster is small, hence the distance from cluster head to Sink is increased and result in increasing the energy consumption of cluster heads, there will consume larger energy after 1800 rounds. The two situations have larger average energy consumption, which result in smaller network residual energy ratio and the survival node number ratio. When the size of cluster is moderate, the network has maximal residual energy and the number of survival nodes. After analyzing the simulation results, we obtain that when k=5, namely the optimal number of nodes is 225.

Setting optimal cluster number is helpful to balance the entire sensor network energy consumption. And setting 225 as the node number, the formula of cluster number in this paper is cluster number = survival node number×cluster number ratio.

We set the cluster number ratio from 0 (when the cluster number ratio is 0, namely the network has only one cluster) to 1 and the interval is 0.1, the simulation results of the survival node number and network residual energy are shown in Fig. 7 and Fig. 8.

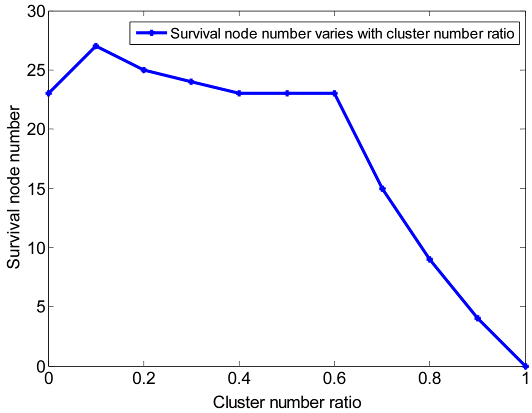

Fig. 7. Survival node number varies with cluster number ratio

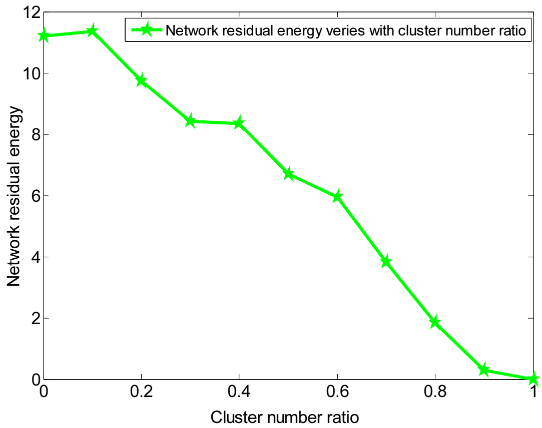

Fig. 8. Survival nodes varies with cluster number ratio

From the simulation results, we can obtain that the entire wireless sensor network energy consumption will increase no matter the cluster number ratio is too large or small. When adopting small cluster number ratio, nodes in cluster have long distance from cluster head, which will increase nodes energy consumption and result in increasing network energy consumption; When adopting large cluster number ratio, the average size of cluster is small, hence the distance from cluster heads to Sink node increasing and lead to increasing cluster heads energy consumption, so the energy consumption of the entire WSN will increase after 1800 rounds. According to the simulation results, the network has the maximal number of survival nodes and the residual energy when cluster number ratio is 0.1, so 0.1 is the ideal cluster number ratio.

We adopt 0.1 as the cluster number ratio, 225 as node number and 1800 as the round number, the comparison with 3DAK, LEACH and SEP protocols in the number of survival nodes and network residual energy that the simulation results are shown in Fig. 9 and Fig. 10.

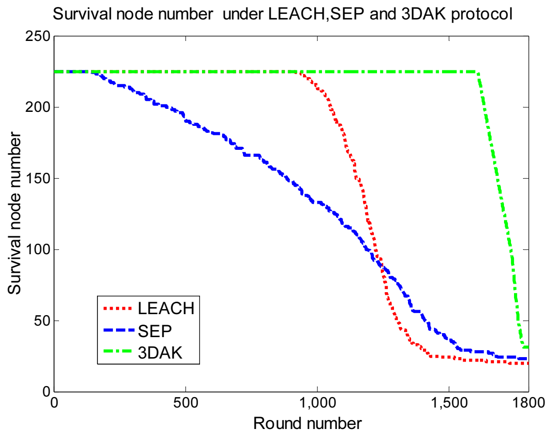

Fig. 9. Survival node number varies with round number under LEACH, SEP and 3DAK

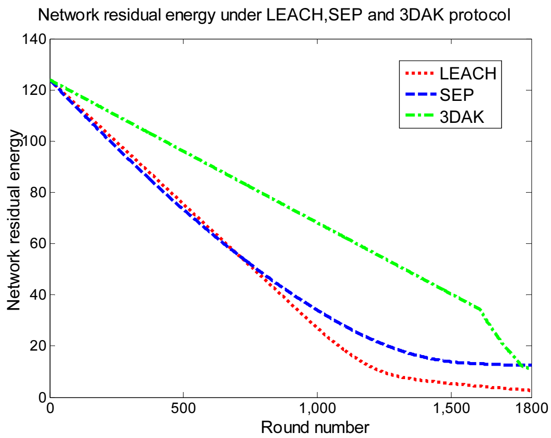

Fig. 10. Network residual energy varies with round number under LEACH, SEP and 3DAK protocol

From the simulation results, we can obtain that 3DAK protocol is superior to SEP, LEACH algorithm in the survival node number and the residual energy. The WSN has no node death and slower rate of residual energy decline before 1600 rounds with 3DAK protocol, which proved that 3DAK can balance energy consumption, effectively save energy and improve the number of survival nodes. To analyze the performance of these three protocols further, the results from the round of first node death and the 50% nodes death are shown in Table 4.

Table 4. The round of first node death and 50% nodes death table LEACH, SEP and 3DAK protocol

protocol	round of first node death(r)	round of 50% nodes death(r)
LEACH	919	1204
SEP	146	1141
3DAK	1609	1720

From Table 4, we can obtain that 3DAK protocol are much better than LEACH and SEP protocol regardless of the round of first node death or 50% of the total nodes death. It's proved that 3DAKA protocol is more balanced in energy consumption and can effectively increase the number of survival nodes.

5 Conclusion

In this paper, we proposed a 3DAK protocol for wireless sensor network which can reduce the energy consumption by optimizing the node density and clustering algorithm. We have obtained the minimum node density through Reuleaux tetrahedron model structured by the intersection of the sensing sphere of the nodes. Then, we have also obtained the optimal node density by simulation with increasing the value of the node density. Moreover, we have optimized the K-means clustering algorithm and obtain the optimal clustering number through the comparing results of the simulation, and the clustering number is changed with the number of survival nodes. Synthetically considering the residual energy of a node and the distance between the node and the cluster center, a cluster head can be selected in a cluster. This cluster head selection algorithm ensures the cluster energy balance. Therefore, the 3DAK protocol is capable of balancing energy consumption and increasing the number of survival nodes comparing by the LEACH and the SEP protocol. In the future, the study of the 3DAK protocol can be extended to large-scale, dynamic wireless sensor networks and improving the energy transmission between nodes.

Acknowledgements

This research is supported by New Century Excellent Talents in University (No. NCET-13-0657) and the State Key Laboratory of Rail Traffic Control and Safety Contract No. RCS2016ZT015, Beijing Jiaotong University. And it is supported in part by the Chinese National Programs for High Technology Research and Development 863 project (No. 2015AA016005).

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