Optimal Cluster Number Selection in Ad-hoc Wireless Sensor Networks

[1,3]Tung-Jung Chan,[1,2]Ching-Mu Chen, [4]Yung-Fa Huang, [5]Jen-Yung Lin and [1]Tair-Rong Chen
[1] Department of Electrical Engineering,
National Changhua University of Education,
Bao-Shan Campus: No.2, Shi-Da Road, Changhua City 500,
Taiwan, R.O.C.
d95621003@mail.ncue.edu.tw
[2] Department of Computer Science and Information Engineering,
[3] Department of Electrical Engineering,
Chung Chou Institute of Technology,
No. 6, Lane 2, Sec. 3, Shanjiao Rd., Yuanlin Township, Changhua County 510,
Taiwan, R.O.C.
{kchen, jung}@dragon.ccut.edu.tw
[4] Graduate Institute of Networking and Communication Engineering,
Chaoyang University of Technology,
168 Jifong E. Rd., Wufong Township Taichung County, 41349,
Taiwan, R.O.C.
yfahuang@cyut.edu.tw
[5] Department of Computer Science and Information Engineering,
Dayeh University,
No. 112, Shanjiao Rd., Dacun, Changhua, Taiwan, 51591,
Taiwan, R.O.C.
jylin@mail.dyu.edu.tw

Abstract: - In clustering-based wireless sensor networks (WSNs), a certain sensing area is divided into many sub-areas. Cluster formation and cluster head selection are well done in the setup phase. With the pre-determined probability and random, every round in the WSNs has the different cluster numbers and cluster heads. However, the well known technique in cluster-based WSN is especially the low energy adaptive cluster hierarchy (LEACH) and its energy performance is improved due to the scheme of clustering, probability, and random. The clustering-based WSN has sensor nodes organized themselves with the pre-determined variable *p* to form clusters. With the pre-determined *p* variable and probability, every round has different cluster numbers which are not the optimal solution. Therefore, in order to evenly consume nodes' energy, this paper proposes a fixed optimal cluster (FOC) numbers that is to analyze the entire network first to have the optimal cluster numbers and then apply it to form the optimal cluster numbers. Moreover, there are two different types of the optimal cluster numbers depending on the location of the base station. One is that the base station is setup at the center of the sensing area. The other is that the base station is setup at the far way of the sensing area. Finally, by the optimization analysis of cluster numbers applied to the ad-hoc WSN before sensor nodes are randomly deployed, the simulation results show the entire network lifetime can be extended very well.

Key-Words: - Ad-hoc Wireless sensor networks, Analysis, Optimal Cluster numbers, Energy efficiency, Clustering-based, Pre-determined variable, Random, Base station location.

1 Introduction

Due to the technology improved quickly [1], sensor nodes are becoming smaller and smaller. With this tiny sensor node, it contains the power supply unit, processing unit, receiver unit, transceiver with amplifier unit and antenna unit as shown in Fig. 1. In recent years, not only the sensor node become smaller, but also it comes with the characteristics of chips smaller and faster, less power needed and transmission distance longer because of the advance technology. By these characteristics of sensor nodes

improved, the wireless sensor networks (WSNs) lifetime can be extended well [2].

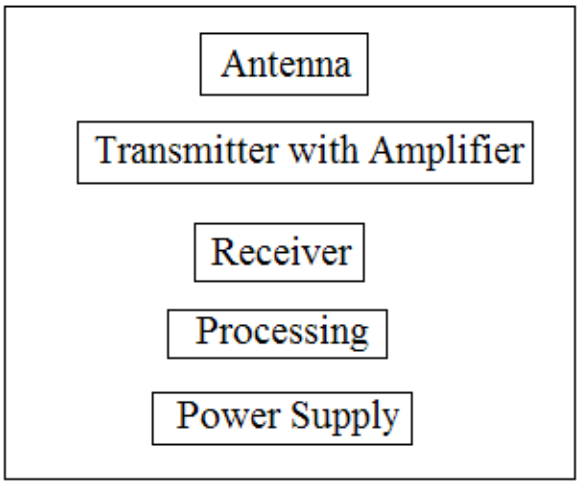

Fig. 1: Architecture of Sensor Node

The main purpose of sensor nodes with the wireless technique [3] is to collect useful data and transmit these data back to the base station for possible needs. These sensor nodes are normally deployed into a certain hardly reachable area to monitor specific event. Hence, the energy of sensor nodes needs to be seriously considered to have longer surveillance.

Traditionally, sensor nodes directly transmit the data to base station and their energy will be drained out very quickly [4] because of the distance constrain. In order not to directly transmit the data back to the base station, the technique [4] [10] of multi-path can have better energy performance compared to the direct transmission technique. That is every sensor node transmits the data to the closer sensor node. However, sensor nodes in these two techniques consume different energy that is sensor nodes consume their energy unevenly [11-12]. The result of these two techniques show some of sensor nodes run out of energy quickly. Therefore, the clustering-based [5] [7] WSN was proposed for unevenly energy consumption of WSNs.

Paper in [6], the Low Energy Adaptive Clustering Hierarchy (LEACH), shows better performance than other techniques. LEACH contains two phases that are setup phase and transmission phase. During the setup phase, sensor nodes are randomly deployed and then these sensor nodes organize themselves into clusters with pre-determined variable p=0.05 for example. During the transmission phase, each cluster contains a cluster head which transmits the data to the base station. Since LEACH uses the probability and random technique, therefore, many papers [7 - 9] compare to the LEACH protocol. However, every round in LEACH will have the different cluster numbers as shown in Fig. 2 which means every round has the different cluster head numbers also shown in Fig. 3. The different cluster numbers [15] in WSNs will make the node numbers in every cluster different and uneven cluster numbers dissipate unevenly energy in each round. Therefore, this paper proposes a fixed optimal cluster number model to extend the entire network lifetime.

Paper in [8] proposed the centralized WSNs that the base station is taken over for all processing and calculating problem so that the entire network performance is much better. That is because the power supply [16] of the base station is city power supply and most of calculations are done here. In this paper, WSNs supplied by the city power is not considered. However, what needed to be considered of power consumption [13] is deploying sensor nodes to the place where the battery of sensor nodes are hard to be recharged and these sensor nodes are organized themselves into clusters. Therefore, to extend the network lifetime via sensor nodes energy [14] saved is much considered in this paper.

Moreover, this paper analyzes the amount of cluster numbers for the entire WSN first. By the optimal cluster numbers applied to the WSNs, the lifetime of WSNs then can be extended very well.

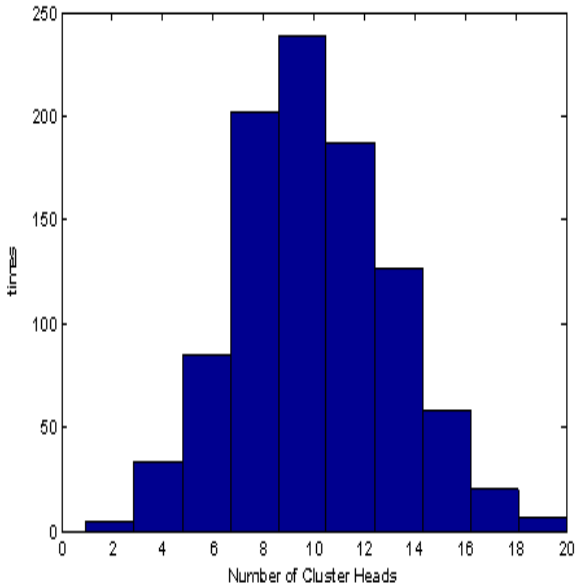

Fig. 2: Distribution of cluster head numbers in rounds.

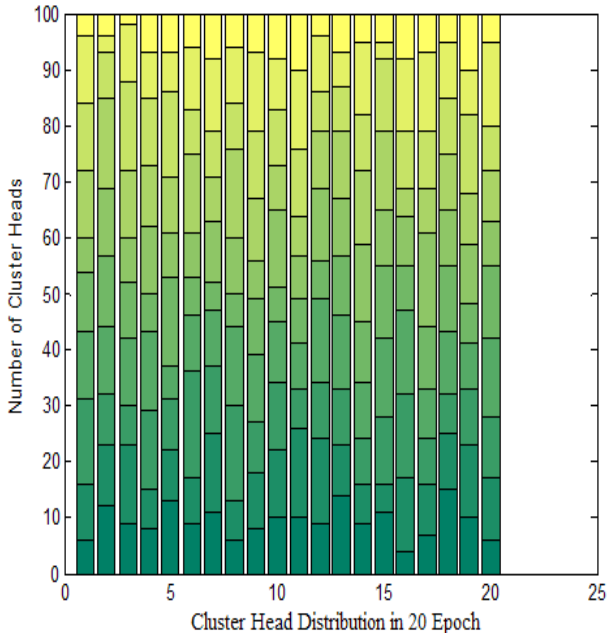

Fig. 3: Distribution of cluster head numbers in 20 epochs.

2 Network Model

As shown in the Fig.1 and Fig. 2, every round contains the different cluster numbers that has different cluster heads [17-19]. Therefore, this paper proposes a fixed optimal cluster numbers for the entire network. In this paper, 2-dimension is assumed. Based on the location of the base station, the optimal cluster numbers are applied to the two different locations that are both the centre of the sensing area and the outside of the sensing area.

The optimal cluster number for the centre of the sensing area is given by

$$k_{opt} = \sqrt{n}\,, \tag{1}$$

where n represents the number of sensor nodes are randomly deployed.

The optimal cluster number for the outside of the sensing area is given by

$$k_{opt} = \sqrt{n}\,\frac{M}{\sqrt{M^2 + 6B^2}}\,, \tag{2}$$

where n represents the number of sensor nodes are randomly deployed, d_0 is the distance from a node to the cluster head, M is the sensing area of x or y axis, and B is the distance from the centre of sensing area to the outside location of the base station.

Moreover, this paper also contains two phases [6] for the entire network that are setup phase and transmission phase. By the setup phase, sensor nodes are organized into clusters with the proposed fixed optimal cluster numbers. With the proposed fixed optimal cluster numbers, every round uses the optimal cluster number to form clusters. During the transmission phase, the data is transmitted back to the cluster head and then cluster head will forward the data back to the base station.

The transmission energy consumption, E_{TX}, from one node to another node is expressed by

$$E_{TX} = l \cdot E_{elec} + l \cdot \varepsilon_{fs} d_{toCH}^2\,. \tag{3}$$

The received energy consumption, E_{RX}, from one node to another node is expressed by

$$E_{RX} = l \cdot E_{elec}\,, \tag{4}$$

where l represents the data (bits) transmitted from sensor nodes to cluster head. Here, assumption of free space d^2 is applied. ε_{fs} represents an amplified transmitting energy in the free space. Parameters used in this paper shown in table 1.

Table 1: Parameters are used in this paper.

Notation	Description
n	Total amount of sensor nodes
E_o = 0.5J/bit	Initial energy for every node
E_{elec} = 50nJ/bit	Per bit energy consumption
E_{DA} = 5nJ/bit	Energy of data aggregation
ε_{fs} = 10pJ/bit/m^2	Amplified transmitting energy
d_{toCH}^2	The distance from a node to the cluster head in free space
d_{toCH}^4	The distance from a node to the cluster head in multi-path
d_0	The distance from a node to cluster head
ρ	Nodes density

3 A Fixed Optimal Cluster Number Protocol

As we can see the architecture of LEACH [6] cannot evenly dissipate the energy of all nodes because of the uneven clusters selection for each round in the network as shown in Fig. 2 and Fig. 3. Therefore, [20] we firstly find the optimal cluster numbers for the LEACH architecture and then use it with the random deployment. However, there are two phases in the network. The first phase is setup phase including sensor nodes randomly deployment, and k optimal cluster number founded for each round. The second phase is transmission phase including TDMA and data aggregation. Fig. 4 [22] shows the proposed fixed optimal cluster number protocol.

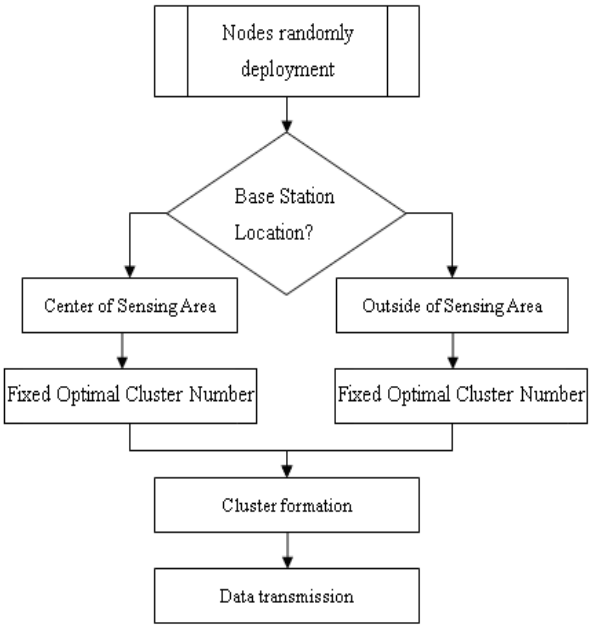

Fig. 4: Fixed optimal cluster number protocol.

The following lists are two phases in the network.

1. Nodes firstly deployed into M x M m region.
2. Given the B.S. location.
3. B.S. is set to the centre of the sensing area; uses the fixed optimal cluster numbers in (1) for the cluster formation phase.
4. B.S. is set to the outside of the sensing area; uses the fixed optimal cluster numbers in (2) for the cluster formation phase.
5. Nodes organize themselves into clusters with the given B.S. location address.
6. Every round will have the same fixed optimal cluster numbers.
7. Data can be sent back to the cluster head and forward to base station with TDMA and data aggregation.

4 Analysis on Optimal Number of Clusters

In clustering-based WSN, a sensing area can be divided into many sub-areas [21-24]. Every sub-area contains a cluster head and many sensor nodes. The cluster head will collect the data transmitted from other sensor nodes; therefore, too many sensor nodes in a cluster will have the more overhead of the cluster head. Similarly, too many or less cluster numbers in a cluster will consume more energy for every cluster head. In order to analyze the two-dimensional WSN, the BS is assumed at two different locations: the centre of the sensing area and the outside of the sensing area.

4.1 Centre of Sensing Area

Suppose that there are n sensor nodes randomly deployed into an M $\times$ M region. In the k clusters WSN, the energy consumption for each cluster head (CH), E_{CH}, and the energy consumption for non-CH, E_{nonCH}, can be obtained by

$$E_{CH} = (\frac{n}{k} - 1) l \cdot E_{elec} + \frac{n}{k} l \cdot E_{DA} + l \cdot E_{elec} + l \cdot \varepsilon_{fs} d_{toBS}^2 \tag{5}$$

and

$$E_{nonCH} = l \cdot E_{elec} + l \cdot \varepsilon_{fs} d_{toCH}^2 , \tag{6}$$

respectively. In (5), E_{DA} represents the energy needed for data aggregation, ε_{fs} represents the sensing environment in the free space and d_{toBS}^2 represents the distance of nodes to the base station in the free space. Therefore, the energy dissipated in a cluster per round, $E_{cluster}$, is expressed by

$$\begin{aligned} E_{cluster} &= E_{CH} + \left(\frac{n}{k} - 1 \right) E_{nonCH} \\ &\approx E_{CH} + \frac{n}{k} E_{nonCH} , \end{aligned} \tag{7}$$

Due to that the base station is set at the centre of the sensing area and the distance between the CHs and the BS, d_{toBS}^2, is given by

$$d_{toBS} \le d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} (:= \sqrt{\frac{10p}{0.0013p}} = 87.7058m)$$

The expected average distance from nodes to cluster head is expressed by

$$\begin{aligned} E[d_{toCH}^2] &= \int\int (x^2+y^2)\rho(x,y)dxdy \\ &= \int_{\theta=0}^{2\pi}\int_{r=0}^{\sqrt{\frac{A}{\pi}}} r^2 \frac{1}{A} r dr d\theta \\ &= \frac{k}{M^2}\int_{\vartheta=0}^{2\pi}\int_{r=0}^{\sqrt{\frac{M^2}{k\pi}}} r^3 dr d\theta \\ &= \frac{2k\pi}{M^2}\frac{r^4}{4}\Big|_0^{\frac{M}{\sqrt{k\pi}}} = \frac{2\pi k}{4M^2}\frac{M^4}{k^2\pi^2} \\ &= \frac{M^2}{2\pi k}, \end{aligned} \quad (8)$$

where ρ represents the nodes density. Therefore, the total energy dissipated in the network per round is expressed by

$$E_{rnd} = l\left(2nE_{elec} + nE_{DA} + \varepsilon_{fs}\left(kd_{toBS}^2 + nd_{toCH}^2\right)\right). \quad (9)$$

By (9), we can find the optimal cluster number k given by

$$\begin{aligned} &\frac{\partial E_{rnd}}{\partial k} = 0 \\ &d_{toBS}^2 + \frac{-nM^2}{2\pi k^2}\Big|_{k=k_{opt}} = 0 \\ &k_{opt} = \sqrt{\frac{n}{2\pi}}\frac{M}{d_{toBS}} \\ &\quad = \sqrt{\frac{n}{2\pi}} M \frac{\sqrt{2\pi}}{M} \\ &\quad = \sqrt{n} \end{aligned} \quad (10)$$

However, the average distance from a cluster head to the base station is given by

$$\begin{aligned} d_{toBS} &= \int_A \sqrt{x^2+y^2}\frac{1}{A}dA \\ &= \frac{M}{\sqrt{2\pi}} \end{aligned} \quad (11)$$

Because the base station is setup at the centre of the sensing area, the energy dissipated to the base station is given as shown below.

$$\begin{aligned} E[d_{toBS}^2] &= \int\int (x^2+y^2)\rho(x,y)dxdy \\ &= \int_{\theta=0}^{2\pi}\int_{r=0}^{\sqrt{\frac{A}{\pi}}} r^2 \frac{1}{M^2} r dr d\theta \\ &= \frac{2\pi}{M^2}\frac{r^4}{4}\Big|_0^{\frac{M}{\sqrt{\pi}}} \\ &= \frac{M^2}{2\pi} \end{aligned} \quad (12)$$

4.2 Outside of Sensing Area.

As the base station is located at the outside of the sensing area, the location area that is $(\frac{D_1}{2}, \frac{D_2}{2} + B)$ where D_1 and D_2 represent the distance of x axis and y axis and B represents the distance from the centre of the sensing area to the base station.

Suppose that there are n nodes randomly deployed into an area that is M x M region. The optimal cluster number is k. The expected average distance of x axis and y axis from nodes to cluster head is as shown below.

$$\begin{aligned} E[x] &= \int_0^{L_1} x\frac{1}{L_1}dx \\ &= \frac{1}{2L_1}x^2\Big|_0^{L_1} \\ &= \frac{L_1}{2} \end{aligned}$$

$$\begin{aligned} E[y] &= \int_0^{L_2} y\frac{1}{L_2}dy \\ &= \frac{1}{2L_2}y^2\Big|_0^{L_2} \\ &= \frac{L_2}{2} \end{aligned}$$

$$E[x^2]=\int_0^{L_1} x^2\frac{1}{L_1}dx$$
$$=\frac{1}{3L_1}x^3\Big|_0^{L_1}$$
$$=\frac{L_1^2}{3}$$

$$E[y^2]=\int_0^{L_2} y^2\frac{1}{L_2}dy$$
$$=\frac{1}{3L_2}y^3\Big|_0^{L_2}$$
$$=\frac{L_2^2}{3}$$

$$E\left[d_{toCh}^2\right]=E\left[(x-\frac{L_1}{2})^2+(y-\frac{L_2}{2})^2\right]$$
$$=E[x^2]-L_1E[x]+\frac{L_1^2}{4}+E[y^2]$$
$$-L_2E[y]+\frac{L_2^2}{4}$$
$$=\frac{L_1^2}{3}-\frac{L_1^2}{2}+\frac{L_1^2}{4}+\frac{L_2^2}{3}-\frac{L_2^2}{2}+\frac{L_2^2}{4}$$
$$=\frac{L_1^2+L_2^2}{12} \quad (13)$$

With assumption of $L_1=L_2$, then $L_1=L_2=\sqrt{\frac{M^2}{k}}$. That is $E[d_{toCH}^2]=\frac{M^2}{6k}$. It is different from approaching the cluster region to a circle and a rectangle. Therefore,

$$E[x]=\frac{D_1}{2}$$

$$E[y]=\frac{D_2}{2}$$

$$E[x^2]=\frac{D_1^2}{3}$$

$$E[y^2]=\frac{D_2^2}{3}$$

$$E[d_{toBS}^2]=E\left[(x-\frac{D_1}{2})^2+(y-\frac{D_2}{2}-B)^2\right]$$
$$=E[x^2]-D_1E[x]+\frac{D_1^2}{4}+E[y^2]$$
$$-(D_2+2B)E[y]+(\frac{D_2}{2}+B)^2$$
$$=\frac{D_1^2}{3}-\frac{D_1^2}{2}+\frac{D_1^2}{4}+\frac{D_2^2}{3}-\frac{D_2^2}{2}$$
$$-BD_2+\frac{D_2^2}{4}+BD_2+B^2$$
$$=\frac{D_1^2+D_2^2}{12}+B^2 \quad (14)$$

Suppose $D_1=D_2=M$, we can find the critical value in Equ. (15) for B as shown below.

$$d_{toBS}=\sqrt{\frac{M^2}{6}+B^2}=d_0$$
$$B=\sqrt{d_0^2-\frac{M^2}{6}} \quad (15)$$

Suppose $d_{toBS}\le d_0=\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$ in free-space mode, we can find the optimal cluster number in Equ. (16) described as shown below.

$$E_{rnd}=kE_{cluster}$$
$$=l\left(2nE_{elec}+nE_{DA}+\varepsilon_{fs}\left(kd_{toBS}^2+nd_{toCH}^2\right)\right)$$

$$\frac{\partial E_{rnd}}{\partial k}=0$$
$$d_{toBS}^2+\frac{-nM^2}{6k^2}\Big|_{k=k_{opt}}=0$$
$$k_{opt}=\sqrt{\frac{n}{6}}\frac{M}{d_{toBS}}$$
$$k_{opt}=\sqrt{\frac{n}{6}}\frac{M}{\sqrt{\frac{M^2}{6}+B^2}}$$
$$=\sqrt{n}\frac{M}{\sqrt{M^2+6B^2}} \quad (16)$$

Suppose $d_{toBS} > d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$ in multi-path mode that is $B \geq \sqrt{d_0^2 - \frac{M^2}{6}}$, we can find the optimal cluster number in Equ. (17) described as shown below.

$$\begin{aligned} E_{rnd} &= kE_{cluster} \\ &= kE_{CH} + nE_{nonCH} \\ &= l\left(2nE_{elec} + nE_{DA} + n\varepsilon_{fs}d_{toCH}^2 + k\varepsilon_{mp}d_{toBS}^4\right) \end{aligned}$$

$$\frac{\partial E_{rnd}}{\partial k} = 0$$

$$\frac{-n\varepsilon_{fs}M^2}{-6k^2} + \varepsilon_{mp}d_{toBS}^4 = 0$$

$$k_{opt} = \sqrt{\frac{n}{6}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{M}{d_{toBS}^2}$$

$$\begin{aligned} k_{opt} &= \sqrt{\frac{n}{6}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{M}{\frac{M^2}{6}+B^2} \\ &= \sqrt{n}\frac{\sqrt{6}d_0M}{M^2+6B^2} \end{aligned} \qquad (17)$$

5 Numerical Results

According to the Fig. 5 and Fig. 6, we can see the optimal cluster number is about 2 and 10. Fig.5 represents the location of the base station is at the outside of the sensing area. Fig.6 represents the location of the base station is at the centre of the sensing area.

By the numerical analysis, we have the *k* optimal cluster number is equal to $\sqrt{n}\frac{M}{\sqrt{M^2+B^2}}$ and $\sqrt{n}$.

The simulation environment is 100 nodes deployed into the sensing area. Therefore, the value of *k* is about 2 and 10.

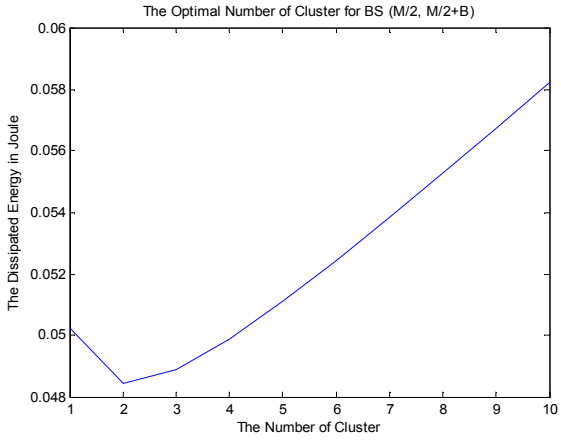

Fig. 5: Energy consumption for every cluster number.

However, as we see if the base station is set to the outside of sensing area which the numerical analysis result is $k_{opt} = \sqrt{\frac{n}{6}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{M}{d_{toBS}^2}$. Therefore, we can compare it to [2] that $4.7980 \geq k_{opt} \geq 1.0057$.

Moreover, after numerical analysis, the precise *k* optimal cluster number is as shown below.

$$D_1 = D_2 = M, B = 125$$

$$\begin{aligned} k_{opt} &= \sqrt{\frac{100}{6}}\sqrt{\frac{10p}{0.0013p}}\frac{100}{\frac{100^2+100^2}{12}+125^2} \\ &= 2.07 \end{aligned}$$

Furthermore, if base station is set to center of the sensing area which is $B = 0$ and k optimal cluster number will be $\sqrt{n}$. Because the total number of sensor nodes is 100, the optimal cluster number will be 10 as the same is Fig. 6.

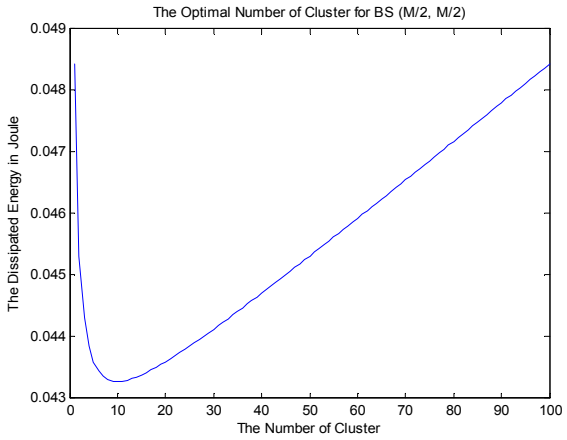

Fig. 6: Energy consumption for every cluster number.

6 Simulation Results

In order to have better simulation result, the simulation tool, Matlab, is used as simulator. In the simulation environment, 100 sensor nodes are randomly deployed as shown in Fig. 7.

Fig. 7: 100 sensor nodes are randomly deployed.

Fig. 8 shows the formation of clusters and how many nodes are still alive there. "o" denotes sensor node is still alive where as "." denotes node is no longer alive and '*' denotes cluster head. Also, sensor node's colour stands for which node belongs to which cluster.

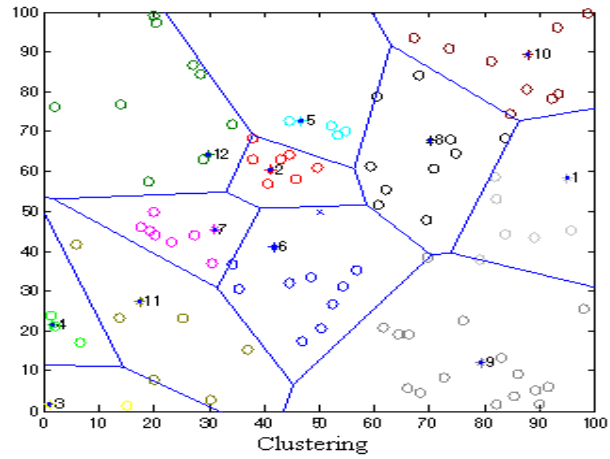

Fig.8: Cluster formation and cluster head selection.

By evaluating 310 rounds in Fig. 9 and 1200 rounds in Fig. 10, numbers of cluster head from both figures are different and nodes' number belongs to each cluster from these two figures are also different. Therefore, by Fig. 10, it shows those sensor nodes closer to the base station will be run out of energy quickly.

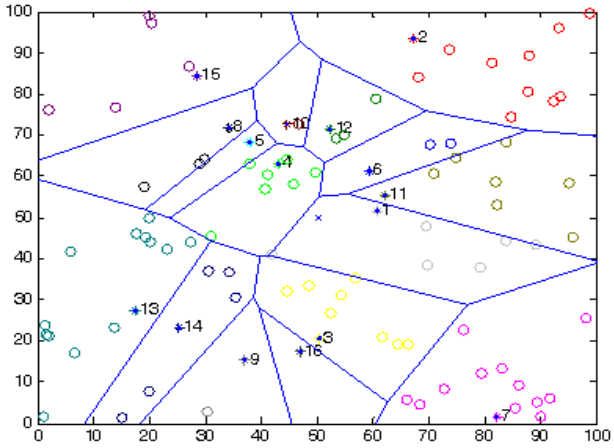

Fig. 9: Sensor nodes are still alive after 310 rounds.

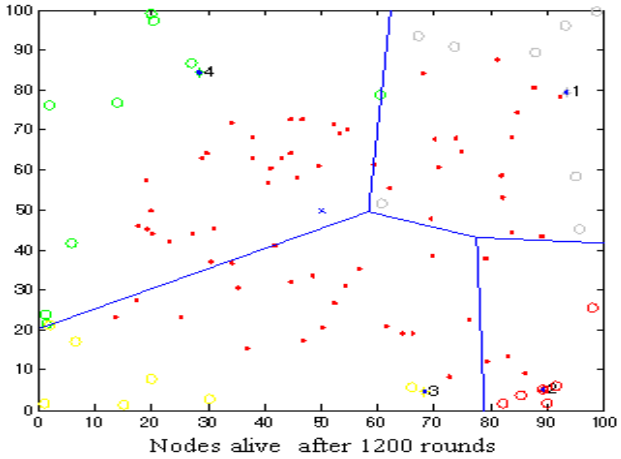

Fig. 10 Sensor nodes are still alive after 310 rounds.

As the base station is set at the centre of the sensing area, Fig. 10 shows how many nodes are still alive and how many nodes are no longer alive. It is obvious that energy usage for nodes far away from the base station is less than those nodes closer to the base station. Therefore, the probability and cluster formation need to be adjusted in order to have the dissipated energy evenly.

Fig. 11 shows that total packets are transmitted from cluster head to the base station. Before the first node runs out of the energy, packets sent from cluster head to base station are the same. However, once first node starts running out of its energy, the total amount of packets to transmit the data back to the base station would be down very fast.

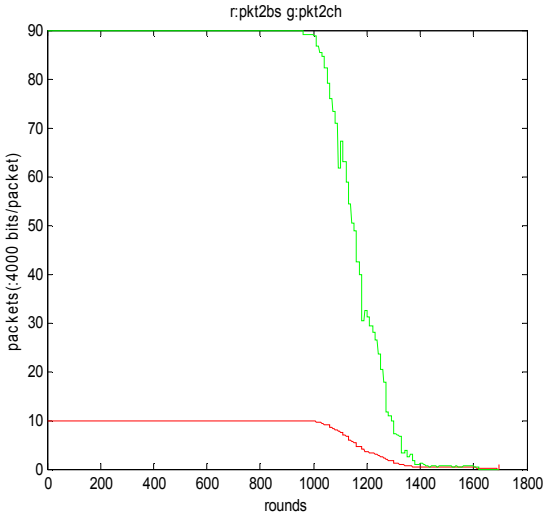

Fig. 11: Total packets are transmitted from cluster head to base station.

However, LEACH with pre-determined variable p =0.05 is applied as shown in the Fig. 12. According to the LEACH architecture, the k optimal cluster number is around from 1 to 5. It is obvious that LEACH with the proposed fixed optimal cluster number = 5 has the better performance.

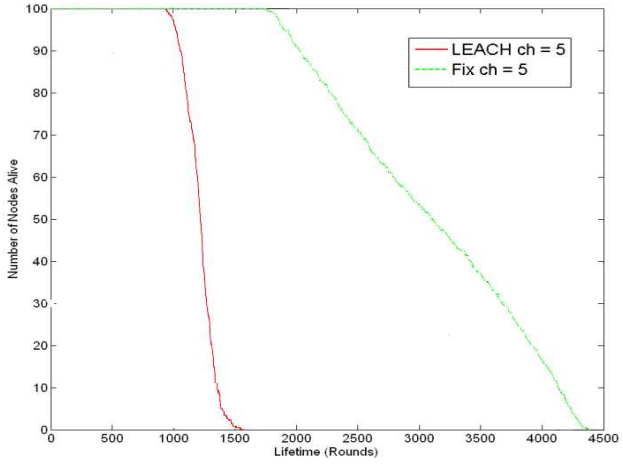

Fig. 12: Comparison between LEACH (p=0.05) and LEACH with fixed optimal cluster head = 5.

7 Conclusion

This paper reveals the proposed fixed optimal cluster number with random and probability in the clustering-based scheme has the better performance. The numerical analysis shows the optimal cluster number is equal to 10 around as the base station is set to the centre of the sensing area and the optimal cluster number is equal to 2 for the outside of the sensing area. Using the proposed fixed optimal cluster number for clusters and cluster heads especially for the architecture of LEACH, the simulation results show the entire network can be extended very well which means the proposed scheme in this paper has much better performance compared to the LEACH architecture in the ad-hoc WSN.

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