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BIO-INSPIRED, CLUSTER-BASED DETERMINISTIC NODE DEPLOYMENT IN WIRELESS SENSOR NETWORKS

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ABSTRACT

The low-cost Wireless Sensor Network (WSN) consists of small battery powered devices called sensors, with limited energy capacity. Once deployed, ACCESSIBILITY to any sensor node for maintenance and battery replacement is not feasible due to the spatial scattering of the nodes. This will lead to an unreliable, limited lifetime and a poor connectivity network. In this paper a novel bio-inspired cluster-based deployment algorithm is proposed for energy optimization of the WSN and ultimately to improve the network lifetime. In the cluster initialization phase, a single cluster is formed with a single cluster head at the center of the sensing terrain. The second phase is for optimum cluster formation surrounding the inner cluster, based on swarming bees and a piping technique. Each cluster member distributes its data to its corresponding cluster head and the cluster head communicates with the base station, which reduces the communication distance of each node. The simulation results show that, when compared with other clustering algorithms, the proposed algorithm can significantly reduce the number of clusters by 38% and improve the network lifetime by a factor of 1/4.

Keywords: Bio-inspired system; Centralized and decentralized clustering; Energy efficiency; Piping; Swarming

1. INTRODUCTION

The wireless sensor network (WSN) consists of spatially distributed low-cost sensor nodes which collect data within the sensing range and transmit them to the Base Station (BS). The BS either accepts the data locally or through the gateway of other networks (Akyildiz et al., 2002). The data collected may be related to environmental conditions, such as temperature, sound, vibration, pressure, motion, etc. The literature survey shows the necessity of WSNs in various applications like: structural health monitoring (Ling et al., 2009), wild life monitoring (Dyo et al., 2013), micro-climate monitoring (Xia et al., 2012), modern power systems (Erol-Kantarci & Mouftah, 2011), smart car parking (Kumar & Siddarth, 2010), etc. The sensor nodes in WSNs are small battery-powered devices with a limited energy source. After deploying the sensor nodes in their sensing field, it is very difficult for the user to replace and maintain the energy source. But there is high possibility to improve the network lifetime by reducing energy consumption. Thereby, the cost of the network will become cheaper.

Hence, energy efficiency is the primary design objective to strengthen the network lifetime of WSNs (Wang et al., 2011). The energy consumption rate can be considerably reduced by various techniques, such as clustering, scheduling, effective routing and efficient data gathering

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and aggregation. Energy aware data-centric routing is carried out by few researchers to improve the energy efficiency (Azar et al., 2010). Compared to data processing, data transmission consumes more power. In such case, the long distance transmission can be controlled to reduce the energy consumption. The primary method to reduce the distance of data transmission among the nodes is clustering (Vivek et al., 2011). In order to support network lifetime through effective network organization, the complete sensing terrain is partitioned into several groups called clusters. Each and every group has a coordinator, signified as the Cluster Head (CH), and the remaining nodes as Cluster Members (CM) (Cheng & Tse, 2011). Two-level clustering hierarchy is illustrated in Figure 1. It is the responsibility of CMs to collect the data and report it their respective CH. The CHs gather and aggregate all the sensed data from its CMs and direct it to the BS directly or via other CHs. Basically, the node with the highest amount of energy is chosen as the CH, which positively supports long-distance transmission to reach the BS. By the selection of best possible number of clusters and cluster heads, network coverage and connectivity could be improved successfully.

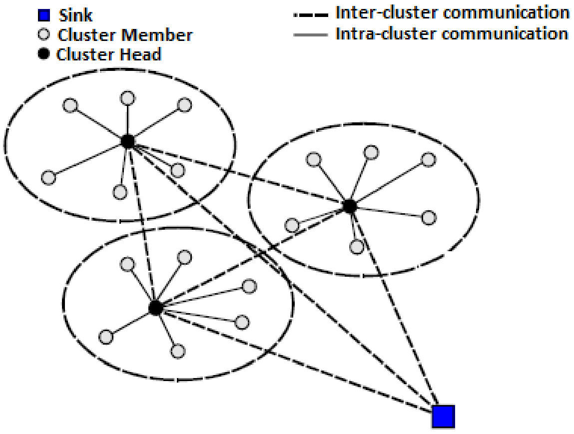

Figure 1 Two-level Clustering Hierarchy

The primary objective of this work is to select an optimum number of clusters for the required area. With the selection of a suitable number of clusters and Cluster Head(s) based on honey comb cluster formation, the energy consumption can be considerably reduced; thereby, the network lifetime can be improved. The rest of the paper is organized as follows. Section 2 presents the related work. Section 3 presents the system model. Section 4 elaborates the proposed clustering algorithm. Section 5 consists of results and discussions. Section 6 comprises the conclusion and future work.

2. RELATED WORK

Recently, many researchers have proposed many clustering algorithms for the WSN. Generally the sensor network's clustering algorithm focuses on cluster management, such as building the right number of clusters, fixing optimal cluster head groupings, managing inter-cluster and intra-cluster data flow. Low Energy Adaptive Clustering Hierarchy (LEACH) is one among the various data flows proposed (Heinzelman et al., 2002). LEACH forms multiple clusters with a single node selected as the CH from each cluster. The CH collects data from its members, combines them into a single data packet and transmits it to the BS. Thereby, the transmission overhead is controlled. Although the decentralized nature of the protocol has a fair protection against intentional attacks, it has limited control over the number of CHs. With the objective of network lifetime improvement, Vergin et al. (2016) have modified the LEACH protocol in such a way, during cluster formation phase that a non-cluster head node will choose a cluster head that lies in close proximity with the center point between the sensor nodes and sink. PEGASIS (Lindsey & Raghavendra, 2002) is another clustering algorithm in which a chain structure is formed using a "greedy algorithm." In this scheme only the Cluster Head (CH) node transmits data to BS. The other nodes transmit their data to a neighboring node. It has control over the CH, but it is vulnerable to attacks and threats. It also comes with a large amount of communication overhead, which limits its scalability.

Researchers have succeeded in using computational intelligence techniques to solve many challenges in WSN (Kulkarni et al., 2011). Saleem et al. (2011) have surveyed the swarm intelligence based the routing algorithm to solve the current issues in WSN. In IC-ACO uses Ant Colony Optimization algorithm to lessen the redundant data in the cluster itself (Kim et al., 2014). Two phases are in this algorithm. The first one is the selection of a cluster. The second phase of the algorithm is related to redundant data transmission in which a specific Sensing radius (*Sr)* is chosen. The nodes within the sensing radius are selected as the CH and others remain in sleeping state. This ant-based optimization mechanism will result in the shortest path to base station by a probabilistic approach.

A honey bee optimization-based routing algorithm has been proposed (Karaboga et al., 2012). Similar to LEACH, the routing mechanism is based on a clustering approach. The cluster head selection and data aggregation is centralized. However, Karaboga et al.'s clustering algorithm differs from LEACH in the CH selection step. In LEACH, CH election is random, but in Karaboga et al. (2012), the honey bee optimization technique has been used for CH election.

The main purpose of the proposed work is to increase the network lifetime by selecting an optimum number of CHs, thereby, selecting an optimum number of clusters. To achieve this honey bee system, the colony management property is followed, which considerably lessens the energy issue in the WSN. From the most interesting behavioral characteristics, such as Foraging behavior, Marriage behavior, and the Queen Bee behavior of honey bees, the Queen Bee behavior is studied in depth to bring up the proposed algorithm, (Senthilkumar & Chandrasekaran, 2011).

3. SYSTEM MODEL

3.1. Energy Model

The first order radio model is considered to be same as Heinzelman et al. (2002). The radio spends the energy ET to transmit b-bit data to a distance *'d'* as shown below in Equation 1:

$$E_T(b,d) = E_{T\text{-}elec}(b) + E_{T\text{-}amp}(b,d)$$

$$\begin{cases} bE_{elec} + \varepsilon_{fs} bd^2 & d < d_r \\ bE_{elec} + \varepsilon_{mp} bd^4 & d \geq d_r \end{cases} \tag{1}$$

where, $d_r = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$, which is the reference distance from transmitter to receiver, E_{elec} is the electronics energy, ε_{fs} and ε_{mp} are the amplifier coefficients in the free space and multi-channel fading model. The radio spends energy E_R to receive *b*-bits of data which is given by Equation 2 as shown below:

$$E_R(b) = E_{R\text{-}elec}(b) = b\,E_{elec} \tag{2}$$

The common assumptions about the proposed sensor network model are:

1) All the sensor nodes are homogeneous.
2) Same initial energy is considered for all the nodes, but the BS is with unlimited energy.
3) BS is placed outside the sensing terrain.
4) The sink and the sensor nodes are all static after deployment.
5) The links are symmetric. Based on received signal strength any node can calculate the approximate transmission distance to another sensor node.
6) The nodes are not re-charged after deployment. Hence, energy efficient algorithms are necessary to reduce energy consumption.
7) The sensing range and transmission range are not equal.

4. BIO-INSPIRED CLUSTER BASED DEPLOYMENT ALGORITHM

In this paper, a cluster-based deployment algorithm is proposed, based on a honey comb formation, with the objective being to improve the network lifetime. The proposed energy efficient clustering algorithm is both centralized and decentralized in nature and it is divided into two stages. As explained in Section 4.1., during the centralized cluster initialization stage, one cluster is developed as a single colony, with an inner cluster head (CH_i) for the entire sensing terrain. CH_i is similar to a Single Queen to control the entire honey comb. CH_i selection is handled by the base station and therefore, it is centralized. During decentralized, swarming and piping-based clustering stage, some additional nodes become CHs by releasing vibratory signals around the inner CH, as explained in Section 4.2. The second stage is decentralized because, CH selection is without the intervention of the base station and it is purely triggered by the sensor nodes themselves. Firstly, 100 nodes are deployed at random in a 180×180 sensing terrain. A unique identification is assigned to each sensor node.

4.1. Centralized Cluster Initialization

The centralized cluster initialization stage is purely centralized in nature. At first, all of the sensor nodes are considered as normal nodes, N. The BS broadcast REQ signals to all nodes in the sensing terrain. The sensor nodes send the response message to the base station, which helps to calculate *Fch*. The sensor node whose *Fch* value is determined to be at a maximum is selected as CH_i. *Fch* is based on energy ratio and distance between the sensor node to BS. On the above basis, the fitness function for CH is set as shown in Equation 3:

$$Fch = (F1_{CH}, F2_{CH}) \tag{3}$$

where;

$F1_{CH}$: Fitness function based on maximum energy ratio E_{rat}
$F2_{CH}$: Fitness function based on distance of sensor node to BS

E_{cur} is the present energy of a node at a time period of T_i. The sum of all nodes E_{cur} is the total network energy E_{tot} at T_i. E_a, which is the average network energy (E_{tot}/N) and it is calculated in Equation 4 as follows,

$$\begin{aligned} E_{rat} &= \frac{E_{cur}}{E_a} > 0 \\ F1_{CH} &= max\,(E_{cur}/E_a) \end{aligned} \tag{4}$$

The node from the middle layers of the circle, having a higher E_{rat}, has the highest probability to become CH_i. The main purpose in the selection of CH_i as the middle layer node is as follows in Equation 5. The base station is positioned anywhere outside the sensing terrain. If the sensor node from the circle's center is chosen as CH_i, then definitely its communication distance with respect to the base station could be optimal. Hence, the node from the center of the circle is fixed as the best node for the second fitness factor $F2_{CH}$.

$$F2_{CH} = \textit{optimum (communication distance between BS to sensor node)} \tag{5}$$

Thus, the selected CH_i will broadcast a message CH_ADV to the nearby nodes within its transmission distance. The nodes receiving this message from the CM for that particular CH_i, is explained in below flowchart, Figure 2a.

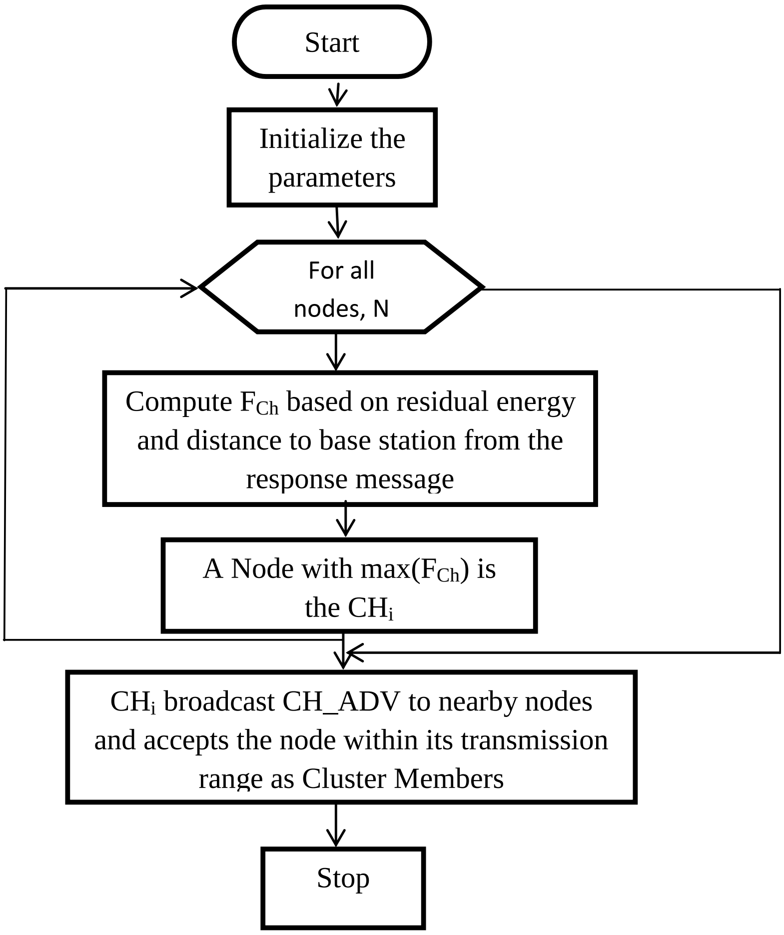

Figure 2a Flowchart of the centralized initial cluster formation algorithm

4.2. Decentralized Clustering

However, after some time New Queens emerge from the old comb to form new colony of honey bees. To invite workers towards the newly formed combs and hold everything under their control, they release a special vibrating signal called piping, Usually, if there is more than one queen in a hive, some candidates among other bees from the comb will progressively get extra pheromone to turn into the Queen Bee. Henceforth, these newly attained new queens will move out of the primary colony and develop secondary colonies in their control. A similar method is followed in the WSN for the new cluster formation.

At the beginning there is one CH_i for the entire network area of radius R_m. Proakis (2000) explains that from the Friis Equation, the transmission range of the CH_i is expected to be as shown below in Equation 6:

$$R_{max} = \frac{\lambda}{4\pi}\left\{\frac{P_t G_t G_r}{P_r}\right\}^{1/2} \tag{6}$$

The R_{max}, transmission range at 2400MHz and R_m are in the ratio 2:3 with the following assumptions,

P_r : *receiving power* = -105 dBm
G_t : *transmitting gain* = G_r = 1.2 dBi
P_t : *transmitting power* = +5 dBm

Since $R_m > R_{max}$ the whole network cannot be roofed under a single cluster with one CH_i in the center. So in the proposed algorithm, a few clusters are formed around the inner cluster with a single CH in each cluster, with an optimum fitness function. The new CHs should be within the transmission range of CH_i (R_{max}). Only then can the CH_i be connected to BS through new CHs. In general, the sensing range (R'_{max}) for the sensor node is less than when compared to the transmission range, as shown in Equation 7 below (Yan & Yuanwei, 2012):

$$R'_{max} = R_{max}/2 \tag{7}$$

The inner cluster area is based on R'_{max}.

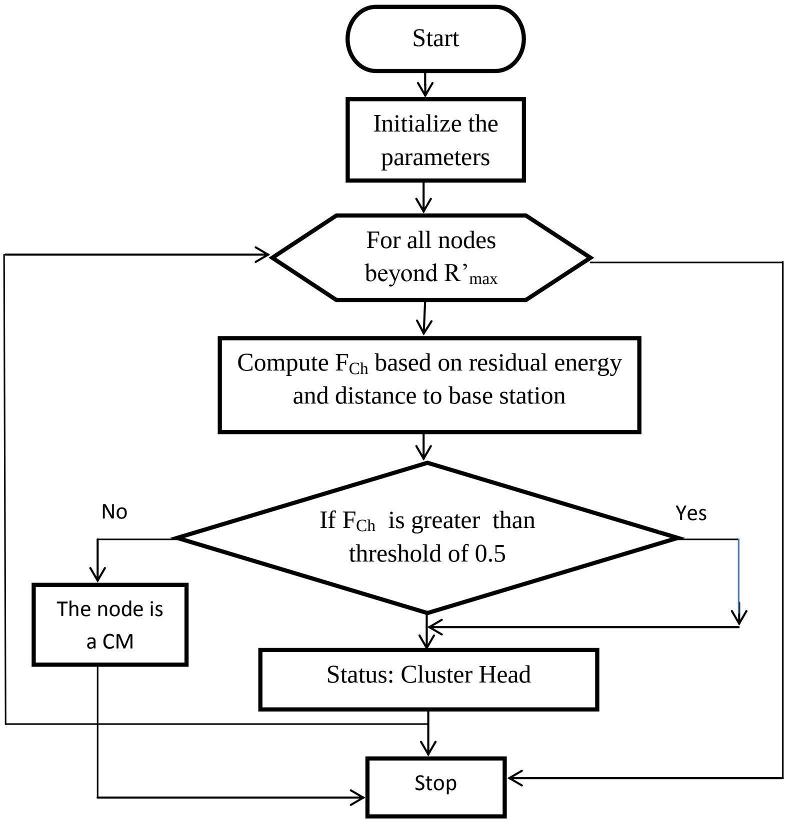

Figure 2b Flowchart of the decentralized clustering algorithm

The nodes beyond R'_{max} will re-group to form new clusters. CH selection happens again as specified in the decentralized clustering algorithm in the below flowchart, Figure 2b. The number and location of the CH should be in such a way that the Total Energy Utilization (TEU) of the network must be at a minimum. For both intra-clusters and inter-clusters, the communication model is assumed to be a one-hop. The optimum distance from the node to the inner CH is shown below in Equation 8:

$$F2_{CH}=\textit{optimum (distance between node to inner CH)} \tag{8}$$

Thus obtained cluster numbers from the proposed bio-inspired algorithm is checked with the Q_{opt} (optimal number of cluster formula) as shown below in Equation 9, (Kim et al., 2005):

$$Q_{opt}=\left\{\frac{.5855NEf_s a^2}{E_{mp}R'm^4-E_{elec}}\right\}^{1/2} \tag{9}$$

Figure 3 below shows a sample of such an optimum cluster formations.

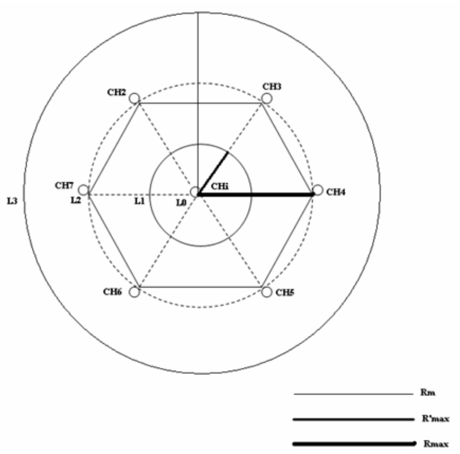

Figure 3 optimum cluster formations

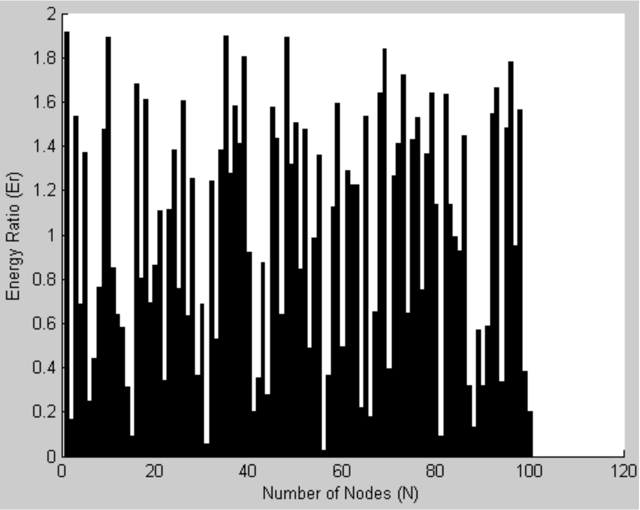

Figure 4 Energy ratio of individual sensor node

5. RESULTS AND DISCUSSION

MATLAB is used to simulate and evaluate the performance of the swarming and piping-based centralized and decentralized clustering algorithm for 300 rounds. The network consists of a total number of ‘N’ nodes which are randomly deployed in 180×180 square regions. The simulation parameters are given in Table 1.

Table 1 List of parameters and their values

Parameters	Value
Number of nodes (N)	100
Side of square terrain ($2a$)	180 m
Transmit amplifier (E_{mp})	0.0013 pJ/bit/m^4
Amplifier constant (E_{fs})	10 pJ/bit/m^2
Distance between CH and BS ($R'm$)	105 m
Electronics Energy (E_{elec})	50 nJ/bit
Cluster Radius (R'_{max})	30 m
Transmission range (R_{max})	60 m
Initial Energy	1 J
Broadcast packet size	10
Data packet size	256 Bytes

Figure 4 shows the energy ratio of each sensor node. The node with higher energy ratio has the highest probability of becoming a CH for the cluster initialization phase. The energy ratio (E_{rat}) is then calculated, which is the ratio of the current energy of each node to the average energy of the network. Maximum E_{rat} is considered as the first fitness factor for inner CH_i selection. The second fitness factor to select CH_i is the optimum distance between sensor nodes to BS. So the center node (0th node) has the highest possibility to act as CH_i.

For analytical purposes, assume BS is outside the sensing terrain. Then, 10 sensor nodes around the centroid of the target region are randomly selected and the distance towards the base station is calculated and plotted as shown in Figure 5. It is clearly indicated that if only the sensor node is at the center of the network then its distance to BS could be less. This will considerably reduce the energy dissipation. Hence, it is confirmed from Figures 4 and 5 that the node at the center of the sensing terrain is selected as CH_i. The idea behind the selection of the center node of the sensor terrain as the initial cluster head is that only the centre node is of optimum distance to BS, provided BS is anywhere outside the sensing terrain.

In Figure 6, the optimal number of clusters formed is plotted against the number of sensor nodes. The simulation and mathematical model results are given in the graph, which shows both models are approximately equal. The nodes with considerable residual energy are selected as the CH. The selected CH could either communicate directly with BS or through a multi-hop.

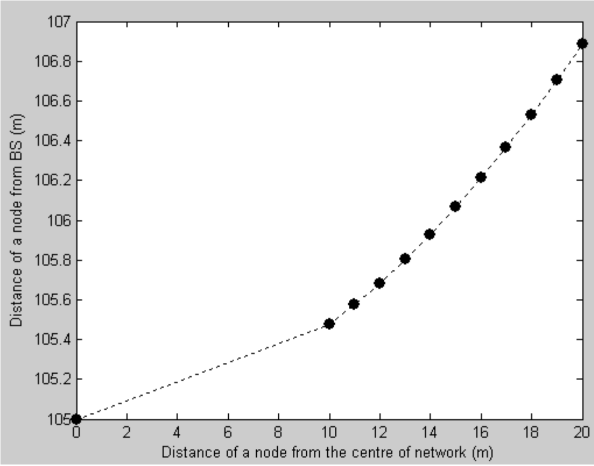

Figure 5 Distance of a node from center of the network versus distance of a node mathematical model from BS

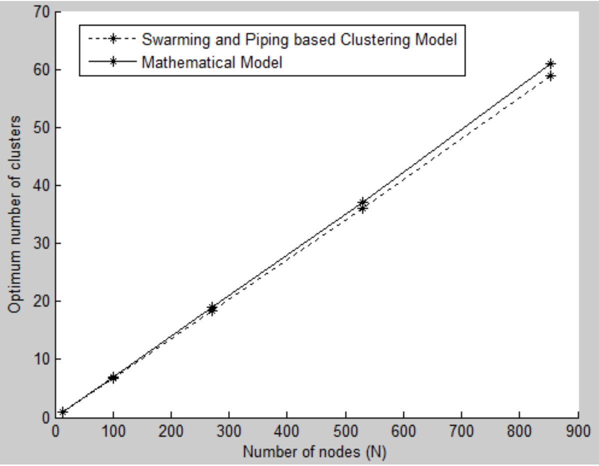

Figure 6 Cluster formation based on mathematical model

In general the cost of the network will be considerably less, if the numbers of nodes are optimal. If the numbers of clusters are at an optimum, then the optimal sensor nodes could also be compromised. In Figure 7, the result is compared with the work of Kim et al. (2005). When N = 100, the optimal number of the CHs is between 1 and 11 formula (Kim et al., 2005). But, in this bio-inspired swarming and piping-based clustering model, the number of CHs is below eight for N = 100.

For energy efficiency purposes, the network lifetime has to be sustained over a period of time. The network lifetime guarantee can also be obtained by measuring the remaining energy, based on number of nodes in the network. In Figure 8, the data prove that there is substantial improvement in the network lifetime compared to LEACH protocol. After cluster formation, the average residual energy of the network is marked against the number of clusters. It shows that the bio-inspired swarming and piping-based clustering model, balances the energy consumption among CHs.

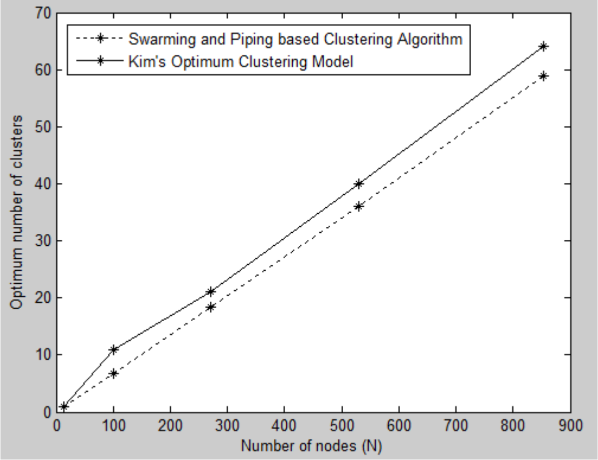

Figure 7 Number of clusters versus number of nodes

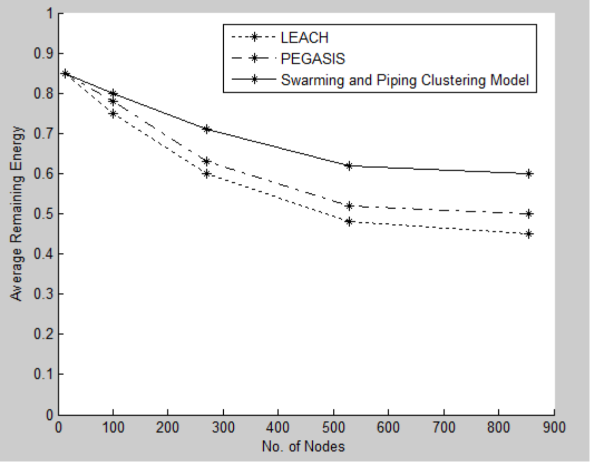

Figure 8 Average network energy versus number of nodes

6. CONCLUSION

In this paper, a novel bio-inspired swarming and piping-based clustering algorithm is proposed to improve the sensor network lifetime. In the LEACH protocol, since the CH selection is random, network lifetime will not always be stable. In this proposed algorithm, the sensor node with its maximum residual energy and with an optimized distance to the sink node will become CH_i in cluster initialization phase. During the decentralized swarming and piping-based clustering phase, sensor nodes with higher residual energy and within the transmission range of CH_i will become outer CHs. Simulation results show that the proposed algorithm acts better than other protocols in optimizing CHs' energy consumption, extending their network lifetime by a factor of 1/4. Progress is being made towards a more energy efficient algorithm where in each cluster a substitute node is scheduled to fill the space of the actual CH if its energy level drops below the threshold value. Hence, the CH re-election process will be handled in the future, which could further improve the connectivity and network lifetime. It is further planned to extend the work through on-demand optimal scheduling to improve the network reliability.

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