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Optimal Cluster Size for Wireless Sensor Networks

Ahmed Sohoub
Misurata University/IT Faculty, Misurata, 218512, Libya
Email: a.sohoub@it.misuratau.edu/ly
ORCID iD: https://orcid.org/0000-0002-5757-0210

Salem Sati*
Misurata University/IT Faculty, Misurata , 218512, Libya
Email: salem.sati@it.misuratau.edu/ly
ORCID iD: https://orcid.org/0000-0002-6062-497X
*Corresponding Author

Mohamed Eshtawie
Libyan Academy for Postgraduate Studies/Computer Science Department, Misurata, 218510, Libya
Email: m.eshtawie@it.misuratau.edu/ly
ORCID iD: https://orcid.org/0000-0000-0000-0000

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Abstract: Since energy consumption is one of the main challenges in wireless sensors networks performance and efficiency, this paper discusses and proposes a mathematical model that compromises these two crucial parameters. In addition, number of clusters, cluster size, and number of cluster heads all contribute in network robustness; they have been studied and manipulated in details. This paper suggests a mathematical model that calculates and finds the optimal cluster size and number of sensors for Low Energy Adaptive Cluster Hierarchy (LEACH) protocol. Wireless Sensor Network (WSN) is a network includes devices (sensors) for collecting data by sensing the field. Clustering is one of the simplest strategies used to minimize the power lost in WSNs. Its performance is affected by network area and number of sensors. The cluster head is elected based on traditional Low Energy Adaptive Cluster Hierarchy protocol. The optimal cluster number is detected based on the condition of the LEACH delivery ratio. NS2.35 and MannaSim framework are applied for validating the proposed model. The results show that the proposed model is approved at different areas and nodes density. The optimal cluster size obtained by the proposed model is equivalent to optimal clusters number for 100 % delivery ratio of LEACH.

Index Terms: Optimum Cluster Size; Optimum Clusters Number; Optimal Cluster Ratio; Packet Delivery Ratio; Cluster Head Selection.

1. Introduction

Nowadays, Wireless Sensor Networks (WSNs) are used in different life scenarios. Tracking and monitoring are considered as two main fields of these scenarios. Moreover network topology changes based on node mobility, and activation and deactivation. In other words, tracking and monitoring are considered as two main fields of WSN scenarios. To fulfil these functions, sensor nodes are placed in a distributed manner throughout the zone, so that they collect data from their active region and transmit it to the base station (BS). In their nature, sensor nodes are small in size and get their energy from batteries, which lead to short life time of the network due to sensor limited life time. Since it is not possible to recharge or replace batteries, the key question is how to increase WSN lifetime by determining the optimal cluster size.

Dividing sensors to clusters, that has many nodes for collecting data from sensing area, can be good answer to this question. Among these nodes in cluster, one is called master node and is responsible for managing the cluster, it is called cluster head (CH). For improving the performance of the single cluster, data gathering and transmission are distributed fairly among all cluster nodes. Sensor nodes in a cluster send their collected data to the selected CH. As a result, CHs aggregate and transmit their data to the BS either in multi-hop or single-hop. Single- hop usually concerned with inter-cluster transmission where sensor nodes are directly connected to their CH. Intra-cluster communications are done among CHs where they send data to the BS.

The optimal cluster is important to trade-off between data aggregation and energy consumption. The model is based on the delivery ratio metric. It considers the network density as a function of area and number of nodes. The rest of this paper has the following parts: Section 2 explores researches related to WSN cluster topic. Section 3 presents the need for optimal cluster size. The following Section 4 discusses the parameters impacting the optimal cluster size. While Section 5 presents the proposed model, it presents assumptions and variables. Section 6 demonstrates the mathematical equations of the proposed model. In Section 7, the simulation scenarios of the proposed model are investigated. Section 8 concludes the paper and provides suggestion for future work.

2. Related Work

Energy consumption is considered to be one the most challenges in WSN clustering. It is highly affected by cluster size therefore, different researches tried to find the optimum cluster size for low energy consumption. Low Energy Adaptive Clustering Hierarchy [1] is the common clustering algorithm that is used for routing in WSN. LEACH aims to minimize overhead and prolong the sensor lifetime. LEACH is designed based on the idea of an equal-size clustering, where sensors locally and randomly decide their decisions of the CH selection. Sensor becomes CH when it has the minimum threshold function value. In other words, sensor's energy and density are not considered when selecting CHs, instead, random variable and probability method are only considered when selecting CHs. The threshold function is calculated based on probability after generating of random value between 0 and 1. The main issue in LEACH protocol is the unfair energy consumption.

LEACH-C [2] is a based LEACH clustering algorithm. In this algorithm, clusters are calculated and centralized at the same time. In this approach, the BS gathers the grid and energy information for all sensors, and chooses the CH as a consequence. In the LEACH-C approach, has the problem of high overhead and energy consumption when selecting the CH, due to the connection between BS and all sensors. In [3] Hybrid Energy-Efficient Distributed (HEED) is proposed as an equal-size clustering approach to overcome the LEACH problem of energy in CH selection. In addition, HEED employs the sensor's distance as the second threshold in CH selection. HEED has the disadvantage of an overhead of sending control messages to directly connected sensors. The work in [4] proposes a Fuzzy-based Energy-Aware Unequal Clustering algorithm (FEAUC). This protocol considers the cluster as circular partitioning to control the energy consumption of sensors and to solve the problem caused by a multi-hop. Performance evaluation of this algorithm is conducted by real scenarios using the low-power mobile sensor node. The applications are consist of sensors powered by limited and unchangeable batteries. Layered Energy Balanced Unequal Clustering and Routing (LEBUCR) for WSN are proposed in [5]. The protocol is proposed to reduce the number of high power transmission since it splits the topology into layers and the cluster head is chosen from layers. To make the LEBUCR efficient irrespective of the base station location, LEBUCR utilizes both flat and hierarchical cluster forming. To eliminate isolated sensors and to reduce routing overhead, intermediate sensors are chosen in the route selection. Simulation scenarios indicate that the LEBUCR outperforms well in terms of network lifetime and scalability.

An energy-efficient unequal clustering approach based on a balanced energy strategy (EEUCB) is proposed in [6]. In this work they concentrate on distance in order to reduce energy loss. In EEUCB a sleep wake method is utilized together with the initial sensor energy and double cluster head. Furthermore, EEUCB has a clustering strategy based on two phases, namely intra- and inter-clustering methods. When compared with other techniques, the results show that EEUCB protocol has better lifetime improvements when compared with LEACH and other similar protocols. The protocol proposed in [7] named an Energy-Efficient Unequal Chain Length Clustering (EEUCLC), where the CH selection is a probability-based decision. Based on the sensor's residual energy and their location distance from the BS, some sensors are chosen as CHs candidate. After selection, CHs reduced their transmission range according to their displacement from the BS. In [8] researchers proposed Novel-LEACH. In WSN, routing is a resource- consuming task. This is new energy-efficient clustering protocol for WSNs. This protocol was designed based on the employment of Particle Swarm Optimization (PSO). The clustering is implemented with the target of minimizing the intra-cluster displacement with combining the optimizing of the energy usage.

In [9] Degree and Contact Epidemic protocol (DC-Epidemic) is proposed. This protocol is based on the message copy that occurs when the number of directly connected nodes is equal to a calculated threshold. It is an energy-aware routing protocol for an OppNet network. When validated, the results show that DC-Epidemic protocol improves the delivery ratio and reduces the overhead of the traditional epidemic protocol. The work presented in [10] is a study and investigation of message copy with contact information by considering the energy consumption. The Simulation results show the impact of energy and contact parameters on each other. In [11], the strategy proposed is designed based on dynamic replication that can be deployed with virtually utility function. When examined in real-life networks, the paper shows that the strategy reduces replicas in networks by increasing delivery efficiency.

The work presented in [12] is a survey provides a comprehensive review of LEACH clustering protocols. This survey is a study that classifies LEACH protocol approaches based on CH selection, data gathering. ESO-LEACH protocol is proposed in [13]. The results obtained for the ESO- LEACH algorithm show that the lifetime of the network using ESO-LEACH is better than that which using LEACH. [14] Proposes an energy-efficient adaptive distance-based clustering called Adapt-P. This protocol uses an adaptive probability function to formulate clusters. The cluster-head selection probability is adopted at the end of each round based on the maximum number of cluster-heads. The work presents in [15] introduced LEACH-CR protocol. When compared with LEACH, the experimental results in terms of energy loss, dead sensors, and number of packets sent to the base station show that the proposed protocol has better performance. This study in [16] proposes a new protocol called LEACH-G-K that divide the particular area into equal sizes. The simulation results show that LEACH-G-K reduces energy consumption and improves Quality of Service.

3. Need of Optimal Clustering Size in WSN

Cluster size is a crucial point in network performance. Cluster characteristics are concerned with the number of nodes, distance between nodes, and any other consequences such as energy consumption. When constructed by LEACH, clusters are not divided in an optimal way. Therefore, the total energy consumed is increased exponentially. Furthermore, The LEACH performance degraded when the cluster size is not in optimal value. The network lifetime, which is the main aim of the clustering by LEACH is also affected by cluster size. Therefore, optimal cluster value of the cluster number or cluster size is obtained for the following reasons:

1. Dynamic and Fixed Size: Generally clustering techniques are classified into two main types: fixed and dynamic clusters. The fixed cluster size has a fixed number of CHs, and it is not suitable if sensors have different energy resources. It is not suitable when area cannot be divided into equal parts. Dynamic number of CHs is changeable and variable, in which CHs number and sizes is selected randomly. The dynamic cluster number and size leads to unfair load balance which is the idea of hierarchical clustering and LEACH. Whether cluster size sixed or dynamic, we need to find and investigate the impact of optimal cluster size and number on LEACH performance and network energy.
2. Sensing Field: The sensing field area and shape influence cluster overhead and energy consumption. This means that network energy consumption is reduced when decreasing the sensing field. In contrast, minimizing the sensing area by increasing the cluster size, means that the path hops between sensor and BS include multi-hop CH to CH links. This leads to higher energy consumption. In addition, sensing area effects directly network density. Node density increases as the packet delivery ratio decreases. While the idea of clustering is data aggregation with single hop to CH, sensing area and ratio range determine the network density. The number of hops and length from a sensor node to its CH is reduced when changing area of sense. Therefore, determining the optimal cluster size is a challenge for the WSN.
3. Physical and Medium Access Control (MAC) Layers View: in WSN, the transmission power is related to the distance between sensors and CH in single cluster. Therefore, deploying a huge number of clusters reduce energy wastage. As a result of deploying huge number of clusters, an increase in throughput is obtained, which is an indication of LEACH performance as delivery ratio. From MAC layer view, deploying a minimum number of clusters can reduce energy consumption and loss as well, because it decreases the average hop counts between CHs. Moreover, it degrades the LEACH performance by making multi-hop between sensors and CH in a single cluster. Hence it is a trade-off design issue among the communication power in the physical layer and the number of hops in the MAC layer. This ensures the challenge of optimizing the cluster size in WSNs.

4. Optimal Number of Clusters Parameters

So far it is explained that, cluster size and number highly affect the network performance. However, there are many parameters impact an optimal number of clusters in WSN. These parameters are classified into three levels. The first is based on sensor devices such as radio range. The second is related to the network such as area. The last is the cluster such as the communication mode. Following is a description of the factors impact on the optimal cluster size.

A. Node Density

Density is a function that depends on both node and network variables which are radio range and number of nodes respectively. Therefore the cluster size must consider two variables number and radio range of nodes. In addition, the network sensors type either homogeneous or heterogeneous. Furthermore, energy consumption is directly impacted by node density which is the criteria of finding the optimal cluster size.

B. Sensing Field Area

The optimal cluster size impacts by the sensing field area. The shape and area of sensing field influences path hops and mobility model of mobile sensor. Furthermore, the area impacts directly on the node density. Therefore, the sensing area is one of the optimal cluster size parameters.

C. Cluster Ratio

Cluster ratio is the number of nodes in single cluster to the total number of nodes. The ratio in single cluster is affected by the number of clusters and nodes. CH to CH communication increases by minimizing the number of sensor nodes in a single cluster. For large-scale networks, the energy wastage is approximately the same for single and two-hop paths. However, if the network has a huge number of sensors, the optimal cluster size should be increased for reducing energy wastage in a single cluster. The CH to CH communication will be increased as multi-hop instead of a single hop. This leads to an increase in energy wastage between CHs. Therefore, determining the optimal cluster size and number is crucial in WSNs.

D. Single and Multi-hop communication

Multi-hop routing or communication has network coverage area larger than radio range of single nodes. In a radio node and long distance transmission requires high power, and since the transceiver is the major source of power consumption therefore, in some cases multi-hop routing can be more energy efficient than single-hop routing. In this context, and because the energy and performance as a function related to density, in wireless sensors network the optimal cluster size determines whether the communication is single-hop or multi-hop. That is why the optimal number of clusters impacts the communication between sensors and cluster head as a multi-hop or single hop.

5. The Proposed Model

The proposed model will be presented and explained using different variables related to cluster size. The model is designed based on a distributed clustering algorithm. It is built based on the traditional LEACH clustering algorithms in WSNs. With LEACH clustering, optimum cluster size is determined based on the following assumptions and conditions.

1. Model Parameters: In optimum cluster size model (OCSM), the sensor nodes are considered to be homogeneous. These sensor nodes have radio interfaces with limited range RS. This model considers the sensing area as a rectangular i.e. $A = L * W$. In addition, the homogeneous nodes are employed in sensing area A is finite, where the number of sensor nodes is limited to the value of N. The maximum number of cluster heads CH_{max} in this model should be less than $\frac{N}{3}$. Node density is function of the area and the total number of sensor nodes $D(A, N)$. This model assumes that all clusters used to obtain the optimal cluster size OC_{size} are uniformly distributed. The model used to determine the optimum number of clusters OC_{num} based on the condition of optimum delivery ratio DR_o when employing LEACH protocol.
2. Optimal Cluster Condition: For determining the optimal cluster size OC_{size} the cluster ratio CR% should be constant for different densities. Furthermore, the cluster ratio CR% is calculated based on the number of cluster nodes n and total nodes N using this function CR% = n. To satisfy the cluster size we should apply this function CR%. OC_{num} = 1. However, the main condition to determine the optimal cluster number OC_{num} is the optimal delivery DR_o. The value of DR_o should be equal to 100 % when determining the optimal cluster number OC_{num}. In other words, the optimal cluster number OC_{num} is determined when the optimal delivery DR_o equals one. Both OC_{size} and OC_{num} are computed with taking into account that the density changed. The density is computed based on the total number of nodes N or the rectangular sensing area A.
3. Optimal Cluster Variables: For finding the optimal cluster size OC_{size} or number OC_{num}, we should consider the delivery ratio as an indication of cluster optimal value. Based on the idea of traditional LEACH, we should consider the cluster nodes impact on the optimal cluster number OC_{num}. Therefore, the density of nodes will be changed as a parameter of cluster size. Furthermore, we will change the number of clusters which is related to the cluster ratio CR%. Where the optimal cluster size OC_{size} is impacted by the optimal cluster number OC_{num}. Furthermore, the number of cluster heads changed in the dimension of the number of nodes N and area A. We change the value of density $D(A, N)$ by duplication the area A or the total number of nodes N. For determining the optimal value, the model considers the delivery ratio DR% as an indication of optimal cluster number OC_{num}. The optimal cluster number OC_{num} will be constant regardless of density changes $D(A, N)$.
4. Optimal Cluster Number Calculations: For calculating the optimal cluster number OC_{num}, the model uses the cluster ratio CR%. The optimal cluster number OC_{num} mathematically calculated as the inverse of the cluster ratio CR%. Furthermore, this value can be validated practically when the delivery ratio equals one or 100% as DR_o. Finally the ratio between the inverse of the optimal cluster ratio CR and the optimal cluster number OC_{num} should be unity.

6. Mathematics of Proposed Model

The optimal cluster size OC_{size} is determined when the delivery ratio reaches the maximum value. However, the number of cluster nodes **n** will affect the cluster ratio CR% and the number of clusters. The optimal number of clusters

OC_{num} will be constant, when the density changes with the ratio related to area A and the total number of nodes N. Here, the Optimal Cluster Size Model (OCSM) will be implemented to find the optimal number of clusters OC_{num} and size OC_{size}. From modelling assumptions of WSN, the network topology as a mobile WSN that move in particular area, the optimal cluster size OC_{size} is calculated based on the optimal cluster number OC_{num} or by cluster ratio CR_o with the number of nodes N. The value of optimal cluster size OC_{size} is computed as following:

$$OC_{size} = \frac{N}{OC_{num}} \tag{1}$$

Eq.(1) determines the cluster size OC_{size}, and it shows that it is valid only if the optimal cluster number OC_{num} is determined as demonstrates in Eq.(2). The optimal cluster number OC_{num} is governed by DRo equal to one.

$$OC_{size} = CR_0 . N \tag{2}$$

Eq.(2) finds the cluster size OC_{size}, where this equation is applied using cluster ratio CR%, computed when the LEACH protocol delivery ratio is equal to DR_o. Here, the cluster ratio CR% is governed by the total number of nodes N. the model proposed in this work considers the density. Therefore, changing the network density D(A,N) as a function of particular area A and the total number of nodes N. The network density is defined based on radio coverage r_s as given in Eq.(3).

$$D(A,N) = \frac{\pi . r_s^2 N}{A} \tag{3}$$

Eq. (3) of (OCSM) model shows the relation between the density D(A,N) and the sensing area. It is clear that as the sensing area increase, the network density decrease. In addition, the total number of nodes N that effect the number of cluster nodes n, leads to change in value of optimal cluster size OC_{size}. Furthermore, changing the number of cluster nodes n will impact the value of optimal cluster number OC_{num}. Hence applying the condition in Eq. (4), the optimal cluster number OC_{num}, based on delivery ratio is calculated as follow.

$$1 \leq OC_{num} \leq \frac{N}{3} \tag{4}$$

The number of clusters value in each case should be changed according to Eq.(4). The optimal cluster number OC_{num} obtained based on the performance metric of routing which is Packet delivery Ratio (PDR). The relation between optimal cluster number OC_{num} determined by simulation and optimal cluster ratio CR_o is given by Eq.(5).

$$OC_{num} = CR_o = 1 \tag{5}$$

Eq. (5) validates the optimal cluster number OC_{num} with the optimal cluster ratio CR_o. It shows that the optimal cluster Ratio CR_o increase as optimal cluster number OC_{num} decreases. Eq.(6) approves the cluster size is uniformly distributed, where the number of nodes n is the same in all clusters.

$$OC_{num} = \begin{cases} OC_{num} = \dfrac{1}{CR_o} & DR_o = 1 \\ 0 & otherwise \end{cases} \tag{6}$$

Equation (6) can be simplified and solved in terms of the total cluster nodes as in Eq.(7) below:

$$OC_{num} = \begin{cases} OC_{num} = \dfrac{N}{n} & DR_o = 1 \\ 0 & otherwise \end{cases} \tag{7}$$

For deep investigation of finding the optimal cluster number OC_{num} Eq.(8) consider the network density function of the different three scenarios used by the proposed model (OCSM).

$$OC_{num} = \begin{cases} OC_{num} = \dfrac{N}{n} & D(2A, 2N) \\ r_s & fixed \end{cases} \tag{8}$$

7. Numerical Results

Since energy consumption is one of the main challenges in wireless sensor networks performance and efficiency, this paper discusses and proposes a mathematical model that compromises these two crucial parameters. In addition, number of clusters, cluster size, and number of cluster heads all contribute in network robustness; they have been studied and manipulated in details. As a result the relation between density and number of cluster nodes and whether they are uniformly distributed or not?. The proposed model is evaluated applying different densities. The simulation configuration and settings of different three density scenarios are described in Table 1.

Table 1. Simulation Settings

No	Settings	Details
1	NS2 Version	2.35
2	Clusters Model	Uniform Distributed
3	Devices and Density	Scenario 1 of 50 Nodes Scenario 2 of 100 Nodes Scenario 3 of 200 Nodes
4	Cluster Head Selection	Based on Probability
5	Routing protocols	LEACH Protocol
6	Interface type	Wi-Fi 802.11
7	Performance Metric	Packet Delivery Ratio (PDR)
8	Radio Coverage	Fixed 50 m
9	Buffer policy	FiFo Policy
10	Extension	MannaSim Framework
11	Area Changes as Density Variable	100 X 100 m^2 200 X 200 m^2 300 X 300 m^2
12	Number of Cluster Heads CH_{num}	$1 \leq CH_{num} \leq \frac{N}{3}$
13	Optimal Cluster Number Detection Condition	$OC_{num} = CH_{num}$ when $DR_o = PDR = 1$

The performance metric of the LEACH protocol is the work base of finding the optimal cluster number. The NS2.35 simulator is used with MannaSim framework [17] to evaluate the proposed model. The evaluation scenario is performed with three different densities and number of clusters. With each density value, different areas and total number of nodes is applied. To find the optimal cluster number OC_{num}, the network is examined in terms of packet delivery ratio or data collection based on different evaluation scenarios, in terms of area which is:

- $100 * 100$ m^2,
- $200 * 200$ m^2
- $300 * 300$ m^2.

And changing the network density in terms of number of nodes i.e.:

- 50 nodes network
- 100 node network
- 200 node network

Changing the number of nodes, 50, 100 and 200 node, in each area lead to change in density. For finding the optimal cluster ratio CRo Eq. (6), Eq. (7) and Eq. (8) are applied by changing the cluster number based on Eq. (4). Fig. 1 shows the first choice when the number of nodes is 50 nodes, the packet delivery ratio reached 1, when the number of cluster heads is 16. This proposal changes the value of area based on Eq. (3) and Eq. (8). Clearly, Fig. 1 shows the changes of LEACH protocol Packet Delivery Ratio with respect to variant number of clusters. It shows that optimal cluster number is assigned when the PDR of LEACH equals 100%. This optimal cluster number OC_{num} value (16) is repeated even when the area changed and increased. The LEACH protocol packet delivery ratio still has the greatest value.

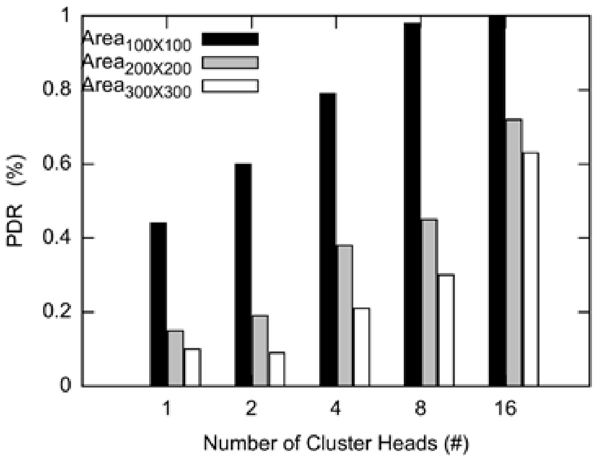

Fig. 1. Packet Delivery Ratio of 50 Nodes

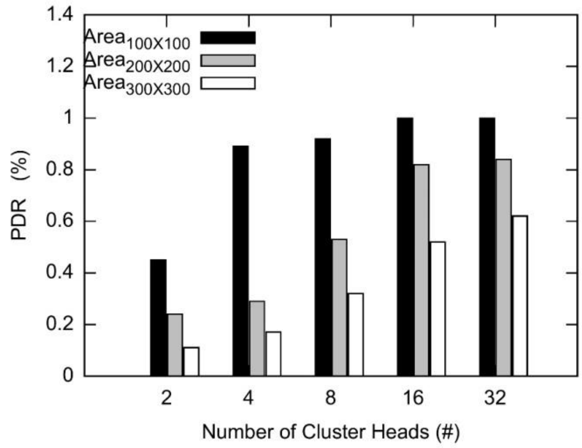

Fig. 2. Packet Delivery Ratio of 100 Nodes

Fig. 2 shows the second choice, i.e. when the number of nodes is 100. It ensures the relation between the optimal cluster ratio CRo and the LEACH protocol packet delivery ratio. The number of cluster heads varies from 2 to 32. This Figure also demonstrates that when the cluster ratio condition is applied, the value of the optimal cluster number OC_{num} is the same as it was in previous case 1 of 50 nodes. To find the optimal cluster size OC_{size} Eq. (2) and Eq. (6) are used and applied. Fig. 2 shows that the optimal cluster ratio CRo is the same regardless the area value. This is not an open sentence, but when the optimal cluster ratio is reached with certain density based on a number of nodes then, this optimal cluster value will be fixed and even repeated when density ratio or value gets higher. In other words, Fig. 2 also shows that when the packet delivery ratio reached 100% it will be fixed at this value even if the number of clusters OC_{num} increased. On the other hand, when the area gets greater, i. e. 200 x 200m^2, the LEACH protocol packet delivery ratio improved when compared with same area of 50 nodes in Fig. 1.

When duplicating the total number of nodes to become 200 node, Fig. 3 shows the result. This result shows that as the area increased, the optimal cluster number OC_{num} is the same. In this case the compatibility between the three figures, i.e. Fig.1, Fig.2, and Fig.3 occurs. In another meaning, when the total number of nodes increased from 100 to 200 node the optimal cluster number OC_{num} is the same as it was in case 1 and case 2. Fig. 3 shows the LEACH protocol PDR of 200 nodes with the different areas applied in case1 and case2. As seen from Fig. 3, the optimal cluster number OC_{num} can be determined when applying the condition of the optimal cluster ratio CR_o. In addition, and from Fig. 3 when the number of clusters becomes less than the optimal cluster number OC_{num}, the LEACH protocol packet delivery ratio as metric will be less than one. By observing the optimal cluster number OC_{num} from three different scenario of Fig.1, Fig.2, and Fig.3, it is found that the optimal cluster number OC_{num} can be determined considering that PDR ratio 100%. The optimal cluster number OC_{num} is equal to 16 clusters for three scenarios of 50,100 and 200 nodes. This approves that the optimal cluster number OC_{num} is uniformly distributed for different three scenarios. Moreover, when considering the condition of CR_o by deploy equation Eq. (5) to Eq. (8), the value of optimal cluster ratio CR_o equal to 0.06 for different three scenarios can be validated.

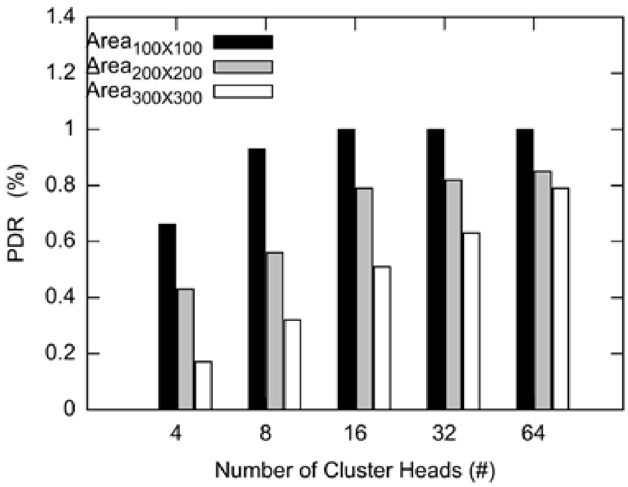

Fig. 3. Packet Delivery Ratio of 200 Nodes

8. Conclusion and Future Work

This paper contributes in proposing a mathematical model to find the optimal cluster number and the optimal cluster size. Throughout this work, the experimental work is done taking into consideration the change in density i.e. changing the number of nodes with respect to area. The proposed model is evaluated applying different densities to find the optimal cluster number. The NS2.35 simulator is used with MannaSim framework for evaluating the proposed model. The number of cluster heads is assigned when the typical packet delivery ratio 100%, is obtained. The model took into account the density impact on the cluster size of the LEACH protocol. When implementing the equations to find the optimal cluster size and number, for three different scenarios the result shows an approval for those equations and conditions. As a future work, study and analysis of the impact of un equal cluster size on LEACH performance can be performed.

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Authors' Profiles

Ahmed Sohoub has a BSc degree in Computer Science from Information Technology Faculty of Misurata University in Misurata, Libya (2012). Eng. Sohoub works as IT engineer with Hatef Libya company since 2013 up to now. He has contributed to several national and International conferences in the areas of data communication. Eng. Sohoub currently is a MSc student at the faculty of Information Technology in Misurata University -Libya.

Salem Sati has a PhD in computer science from HHU University in Dusseldorf, Germany (2017), and an MSc & BSc degree in computer engineering from Higher Industrial Institute in Misurata, Libya (2008 & 1997, respectivally). Dr. Sati has contributed to several national conferences in Libya, Also International IEEE conferences in North America. Asia and Europe in the areas of computer networks. He has many publications in IEEE conferences. He is currently an assistant professor at the faculty of Information Technology in Misurata University -Libya.

Mohamed Eshtawie has received the BSc in computer engineering 1990 from the Engineering Academy Tajoura, Libya. In 1999, he obtained the MSc in Computer Engineering from University Putra Malaysia. In 2008 He received his PhD in the field of signal processing and communication from the National University of Malaysia (2008). Currently he is an Associate Professor at the Libyan Academy Misurata, Libya.

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