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On Global Clustering Algorithm: Layer-Oriented Approach for First/Last Node Dying Applications in Wireless Sensor Networks

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Abstract – *Clustering methods are potentially the framework for power-conserving wireless sensor networks. These methods are among the most effective approaches aiming for prolonging the lifetime. Power-limited nature of the employed devices in wireless networks made the conventional clustering approaches to mainly focus on selecting cluster heads -which are the central points within a cluster- among the nodes with more remaining energy. Periodic rotation of this task -being a cluster head- between nodes leads to distribute the energy consumption. In singlehop wireless sensor network, Hot-Spot problem arises when the further cluster heads to the base station excessively utilize their energy due to the distant communications. The main purpose of this paper is to provide a layering-based clustering algorithm that aims at directly optimizing the nodes' longevity by considering the application in which they operate and the relationship between the width of each layer and its overall lifetime. Two main types of applications are dealt with; First node dying and Last node dying applications. Analytical methods are employed to study the impacts of intra-cluster and singlehop communication traffic loads on the average layer's lifetime that is formulated as an optimization problem.* ***Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords: *Wireless Sensor Networks, Clustering, Layering, Lifetime, Single Hop*

Nomenclature

CH	Cluster head
CM	Cluster member
UB	Upper bound
LB	Lower bound
BS	Base station
NoCL	Number of cluster
AOL	Area of the layer
FND(LND)	First (Last) node dying
CRL	Coverage radius of the cluster
LW	Layer width

I. Introduction

Wireless sensor networks (WSN) are emerging areas of research that have been studied intensively for a few years. Particularly, node clustering has been addressed by many researchers so far and is commonly considered as one of the most promising techniques that simplifies topology management and improves the network's lifetime. Previous studies have shown that organizing the node into clusters will provide better energy efficiency [1]. More over, several WSN applications require only an aggregate value to be reported to the observer. In this case, the gathered data from each node is processed locally and aggregated in a central coordinator referred to as a cluster head (CH) and the redundant data (if any) is omitted to provide more accurate reports about the local region being monitored. In addition, data aggregation reduces the communication overhead in the network, leading to significant energy savings. Node clustering is an efficient network organization in order to support data aggregation and it improves network lifetime [2].

The methodology attributed to clustering algorithms are different. In homogeneous networks, when CHs are just regular sensor nodes, clustering algorithm must be distributed without coordination [3]. In few approaches, a centralized authority (e.g. Base Station) partitions the nodes offline and controls the clusters' sizes in the sense of the number of members; especially, when CHs are rich in resources (e.g. in heterogonous networks). Hybrid schemes can also be found in literatures. The methodology of clustering algorithm in this paper is a hybrid scheme. Base Station (BS) is the centralized authority that partitions the network into layers with respect to nodes' proximity to the BS, while each individual CH takes charge of forming its own cluster in a distributed manner.

In data networks, such as wireless sensor networks, the gathered information from the environment can be reported to the main observer or the sink node periodically or on the event occurrence time.

Clusters of almost the same coverage ranges and node densities handle approximately the same intra-cluster traffic load when a periodic data reporting is assumed. On the other hand, the singlehop communication traffic loads handled by different CHs are not the same since the

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further CHs to the BS have to spend much energy than the closer ones.

At this point, a Hot-Spot problem arises when these nodes excessively utilize their energy due to the distant communications and consequently drain their energy rapidly.

Expectedly, the clustering paradigm increases the burden overloads CHs, forcing them to deplete their batteries much faster than in a non-clustered network [4]. The additional energy consumption is attributed to the aggregation of intra-cluster traffic into a single stream that is transmitted by the CH; and, to the relaying of inter-cluster traffic from other CHs in multi-hop communications. Such relaying is sometimes desirable because of its power-consumption advantage over direct communication (CH-to-sink or singlehop communication).

That makes the implementation of such multi-hop networks feasible in large scale regions. In contrast, the singlehop communication networks, especially those containing homogenous nodes, are mostly applicable in small-scale regions [3].

In this paper, we consider small-scale applications that use singlehop communication for data transmission. We categorize two concepts of network lifetime that are first node dying (FND) and last node dying (LND). In FND applications, the network lifetime is considered as long as the first node dies. That means the network operation is beneficial until all nodes are alive while any node failure would make it useless.

Examples are often seen in applications monitoring crucial events and conditions such as gas monitoring in enclosed or underground car parks for not running ventilator fans all the times but when required. Another example exists in military fields where sensors are monitoring chemical activities and the lifetime of a sensor is critical for maximum field coverage [5]. In such cases any node's failure could possibly consequent a disaster. Other types of applications are the LND applications in which the network lifetime is considered as long as the last node dies. In other words, the network continues its operation until the last node is alive. In these applications, the failure of one or more nodes does not make the network useless.

An example of these applications would be humidity monitoring in greenery. Our main motivation is to introduce an analytical method to develop a hierarchical wireless sensor network that prolongs the nodes' longevity using clustering algorithms.

Innovative approach for this purpose is a Layer-Oriented clustering technique[1] (or briefly layering technique) that aims at organizing nodes into clusters in each layer subject to maximizing the lifetime of that layer which is generally considered as the main criterion. Systematically, the layering technique tends to maximize the lifetime of the first node (last node) in FND (LND) applications. The objective is to determine the optimum cluster sizes to meet the layering criterion. This is achieved by considering the width of each layer directly related to the cluster sizes and consequently the overall lifetime of that layer.

Our contributions are, on one hand, employing the layering technique in the network and derive a mathematical solution for the optimum width of each layer and, on the other hand, to provide an exhaustive comparative study that expands on our previous works in Layer-Oriented clustering approaches in [6]-[7]-[8]. Analytical methods are employed to study the impacts of both intra-cluster and singlehop communication traffic loads on the average layer's energy consumption that is formulated as an optimization problem.

The rest of this paper is organized as follows: Next, in section 2, we provide some related works that have been investigated on the same area. Section 3 describes the system specifications containing energy model, problem statement and layering algorithm. Section 4 details simulation efforts and analysis of the results obtained. Finally, section 5 concludes this paper with directions and scopes of future works.

II. Related Work

In the past few years, many clustering algorithms have been proposed for ad hoc and sensor networks aiming to improve the energy efficiency. Authors in [3] have presented a taxonomy and general classification of clustering schemes, and they surveyed different clustering algorithms for wireless sensor networks and useful comparisons are performed highlighting objectives, features, complexity, etc.

LEACH [9] is an application-specific clustering protocol that utilizes random selection and frequent rotation of CHs for distribution of the total load into all nodes. The clustering process involves only one iteration, after which a node decides whether to become a CH or not and nodes take turns in carrying the CH's role. The data communication in LEACH is based on single-hop communication model. The author also proposed two variants of LEACH, which are referred to as LEACH-C (LEACH-centralized), and LEACH-F (LEACH with Fixed clusters).

EELTC [10] is a new hierarchical clustering algorithm with multihop communication that has the ability of *creating unequal clusters with very low controlling overhead. In this algorithm, a heuristic is proposed in* which the network is divided into radial regions in a centralized manner based on nodes' proximity to BS. Then the BS calculates upper bound (UB) and lower bound (LB) of each layer and results are broadcasted *across the network via a" hello" message.*

All sensors determine their region by receiving the message from the BS. A competitive clustering phase *based* on region and energy is set among nodes to form

[1] *Layering technique is the concept of dividing the network into regions based on a predefined criterion. (For more information see [10].)*

These results show that proposed algorithms for layering the network based on FND/LND applications are scalable in different number of nodes.

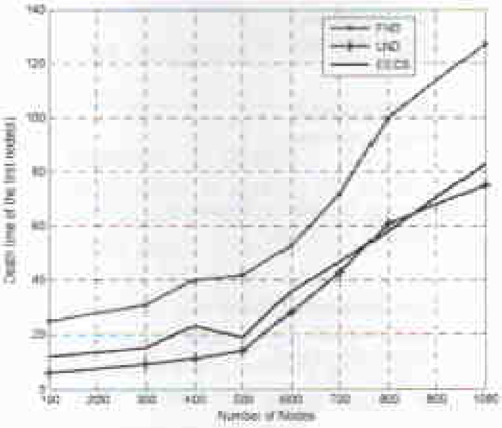

Fig. 10. Death time of first nodes in different nodes density

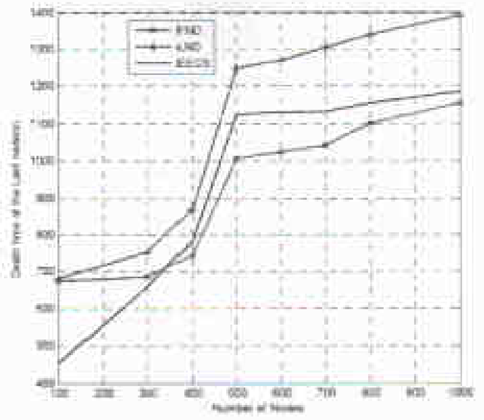

Fig. 11. Death time of last nodes in different nodes density

V. Conclusion

In this article, we dealt with a single hop wireless sensor networks in which nodes were organized into clusters. A Hot-Spot problem arises when furthest CHs excessively utilize their energy due to the distant communications and consequently drain out their energy rapidly. Concerning the outstanding advantages of cluster-based wireless sensor networks, a new analytical layering-based clustering approach in single hop communication WSN has been presented. In this model, a centralized authority (Base Station) is responsible to organize nodes in layers.

Two concepts of network lifetime were categorized in this paper. In first node dying (FND) applications, the network lifetime is considered as long as the first node dies. That means the network is useful until all nodes are alive. Other types of applications are the last node dying (LND) applications in which the network lifetime is considered as the time when last node dies. In other words, the network continues its operation till the last node is alive. Due to the Hot-Spot problem, the nodes in the further layer tend to die rapidly, since they have to consume much energy for long-distance communications. Contrary, the closest nodes are supposed to live longer than others. Based on the above statement, for meeting the basic requirement of the FND applications, nodes are better to be organized so that the lifetime of the furthest layer is maximized. In contrast, for LND applications, it is required to organize nodes so that the closest nodes live as long as possible.

The mathematical approach for layering, on one hand, considerers the type of application (i.e. FND or LND), and on the other hand, calculates the width of each layer so that the basic lifetime-requirements of these applications are met. The lifetime of a layer has been formulated mathematically, in which all kinds of consumed energies by the nodes are considered as a function of the width of the respective layer. This relationship has been modeled as an optimization problem for maximizing the lifetime of the every individual layer.

Therefore, in applications that require FND longevity, the layering algorithm starts from the furthest nodes from the base station, maximizes the lifetime of the furthest layer and calculates the widths of layers iteratively. In contrast, in LND application, the algorithm starts layering from the closest nodes from the base station, maximizes the lifetime of this layer and calculates the widths of other layers.

The performance of the algorithm has been evaluated for an instant network in both FND and LND applications. The Lifetimes resulted from the simulation were close to the mathematical obtained results. That is a fascinating illustration of employing the layering based clustering algorithms in wireless sensor networks. In our similar work, we have focused our attentions to an analytical layer-oriented approach in a multihop communication WSN. Other results showed that for FND applications, the first nodes die much later than those in LND, while for LND applications, the last node dies much later than those in FND.

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exceeding.

The fifth layer could have larger width if there was extra area to be devoted to it.

Death time of first node and last node of each layer is shown in Table IV.

TABLE IV
DEATH TIME OF FIRST NODE AND LAST NODE OF EACH LAYER IN THE FND NETWORK OBTAINED FROM SIMULATION

Layer	The time when first node dies (round)	The time when last node dies (round)
1 (the furthest Layer)	42	59
2	90	114
3	226	300
4	903	1008
5 (the closest Layer)	439	911

Part 2: LND Applications

In these applications, lifetime is defined as the number of rounds taking place as long as any node in layer is alive.

By this definition, maximizing the average lifetime of each layer results in prolonging the lifetime of any individual node, particularly the node tending to die last (in the closest area). Similar to the previous part for FND applications, we run the layering algorithm iteratively in the BS and the calculation of *LWs* results in forming four layers. The results are shown in Table V.

TABLE V
LAYERING PROCEDURE PERFORMED IN BS FOR CALCULATION OF LWS FOR LND NETWORK

Number of layers	r_L	CRL	NoC	Number of nodes in layer	Status
1 (the closest Layer)	223	38.50	3	78	Unallocated area
2	99.62	61.69	4	266	Unallocated area
3	67.18	16.22	22	99	Unallocated area
4(the furthest Layer	50.04	8.57	45	57	Finish

These results are broadcasted across the network and it starts its operation with determined layers. Table VI compares the average lifetimes of layers derived from simulation with those derived from calculation in BS.

TABLE VI
COMPARISON OF AVERAGE LIFETIME FOR EACH LAYER IN THE LND NETWORK

Number of layers	Average LT (from simulation)	Average LT (from calculation)
1 (the closest Layer)	1079.5	1098.8
2	556	689.4
3	77	79.5
4 (the furthest Layer)	17	16.5

The mathematical results match to the simulation results. Table VII shows the death time of first node and last node of each layer obtained from simulation.

TABLE VII
DEATH TIME OF FIRST NODE AND LAST NODE OF EACH LAYER IN THE LND NETWORK OBTAINED FROM SIMULATION

Number of layers	The time when first node dies (round)	The time when last node dies (round)
1 (the closest Layer)	909	1250
2	360	752
3	69	85
4 (the furthest Layer)	14	20

Part 3: Comparison of FND and LND applications

In this part, we answer to this question: Why the layering algorithm starts from the furthest nodes for FND applications and closest nodes for LND applications. We mentioned that, the nodes in the further layer tend to die rapidly since they have to consume much energy for long-distance communications. Contrary, the closest nodes are supposed to live longer than others do. For meeting the basic requirement of FND applications, nodes are better to be organized so that lifetime of the furthest layer is maximized. In contrast, for LND applications, it is required to organize nodes so that the closest nodes live as long as possible. The first row of Table VIII compares the "death time of the first node" in the furthest layers in both FND and LND applications. It is clear that the time when the first node dies in the furthest layer in FND network is much longer than that in LND network. That is why the layering algorithm starts from the furthest nodes in FND applications. Similarly, second row of Table 8 compares the "death time of the last node" in the closest layers in both applications. It is obvious that the last node of the closest layer in LND network lives longer than that in FND network. That justifies the reason of performing layering from closest nodes in LND applications.

TABLE VIII
DEATH TIME COMPARISON OF FIRST NODE AND LAST NODES FOR FND AND LND NETWORKS

	FND	LND
Time when first node of the furthest layer dies (rounds)	42	14
Time when last node of the closest layer dies (rounds)	911	1250

To prove scalability, we measured and compared the death time of first (last) nodes for different number of nodes in FND, LND and well-known algorithm EECS. Fig. 10 presents that first nodes in FND algorithm tend to die later than those in LND or EECS.

That's due to the FND algorithm maximizes the lifetime of furthest nodes, which may die sooner. Similarly, in Fig. 11, death time of the last node(s) in LND algorithm seems to be longer rather than two other algorithms, i.e. FND and EECS; Since LND algorithm maximizes the longevity of the closest nodes, which die later.

Considering the constraint (20) assures that "*exceeding*" is avoided. The algorithm maximizes (16) with respect to CRL_L for each layer L in order to obtain the width of each layer. Fig. 9 is a block diagram that provides a better understanding of layering algorithm.

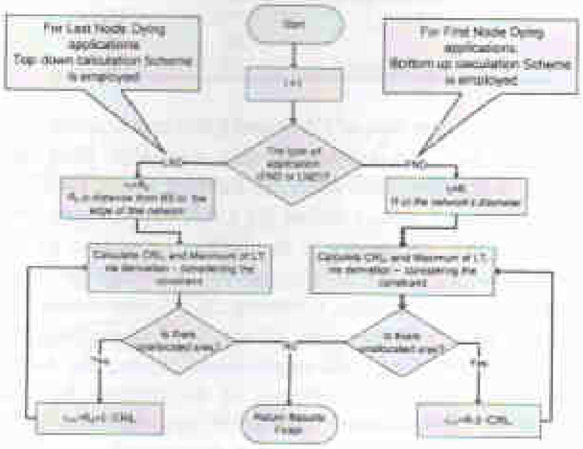

Fig. 9. Block diagram of the algorithm

IV. Evaluation and Simulation Results

The propose algorithm is evaluated in MATLAB. Consider the network covering a Disk-like area, with R=500 (m) and R_c=50 (m). Nodes are uniformly distributed in this region with the density ρ=0.002. Other simulation parameters are listed in Table I.

TABLE I
SIMULATION PARAMETER

Parameter	Value
Initial Energy	0.5 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_{DA}	5 nJ/bit/signal
Data Packet Size (l)	4000 bits
Control Packet Size (l')	8 bits
d_0	87 m

Starting with a single layer network and the parameters above, the Eq. (16) becomes:

$$LT_1 = \frac{\pi CRL_1^2 \times \rho \times E_{init}}{\begin{bmatrix} 2E_{Tx}\left(l', CRL_1\right) \\ +\pi CRL_1^2 \times \rho \times E_{Tx}\left(l', {CRL_1}/{2}\right) \\ +E_{rf}\left(\pi CRL_1^2 \times \rho\right) \\ +\pi CRL_1^2 \times \rho \times E_{Tx}\left(l, {CRL_1}/{2}\right) \\ +\pi CRL_1^2 \times \rho \times E_{Rx}\left(l'\right) \\ +E_{Tx}\left(\tilde{l}, d_{toBS}^1\right) \end{bmatrix}} \quad (21)$$

where d_{toBS}^1 can be determined from (17).

Part I: FND applications

In FND applications, lifetime is measured as the number of rounds taking place as long as all nodes in layer are alive.

By this definition, maximizing the average lifetime of each layer results in prolonging the lifetime of any individual node, particularly the node tending to die first (in the furthest area).

Running the layering algorithm iteratively, five layers are formed one by one.

Table II illustrates the iterations while calculating the LWs.

TABLE II
LAYERING PROCEDURE PERFORMED IN BS FOR CALCULATING LWS FOR FND NETWORK

Layer	r_L	CRL_L	LW_L	NoC	Number of nodes in layer	Status
1 (the furthest Layer)	270.44	14.78	29.56	26	97	Unallocated area
2	235.94	17.25	34.5	20	100	Unallocated area
3	191.2	22.37	44.74	13	109	Unallocated area
4	62.76	64.22	128.44	3	186	Unallocated area
5 (the closest Layer)	50.06	6.35	12.7	12	8	Finish

These results are broadcasted to the network via a beacon. Now, we simulate the operation of network with the determined layers.

Table III compares the average lifetimes of layers derived from simulation with those derived from calculation in BS.

It is clear that the mathematically obtained results are close to the real ones.

TABLE III
COMPARISON OF AVERAGE LIFETIME FOR EACH LAYER IN THE FND NETWORK

Layer	Average LT (from calculation)	Average LT (from simulation)
1 (the furthest Layer)	51.8	50.5
2	107.6	102
3	292.6	263
4	1034.8	955.5
5 (the closest Layer)	560.5	675

Another result that can be inferred from the Table III is that the obtained LT of the closest layer (fifth layer) seems to be less than LT of forth layer; that was basically supposed to have larger amount.

This is due to the constraint applied to the layers, which must limit the last layer's area in order to avoid

At this time, we can calculate the derivation of (16) with respect to CRL_1 and find the exact width of the first layer, LW_1, which is two times of the obtained optimum cluster radius, $CLR_{1\text{-}opt}$:

$$LW_1 = 2CRL_{1\text{-}opt} \tag{18}$$

Two main cases may occur in the layering algorithm. In one case, the determined layer is not wide enough to cover the whole network area, i.e. $LW_1 < R - R_0$. In this case, there would be some "*unallocated region*" or the region that is not covered by layer (see Figs. 8(c) and 8(d)).

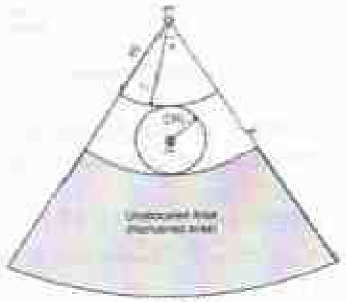

Fig. 8(c)

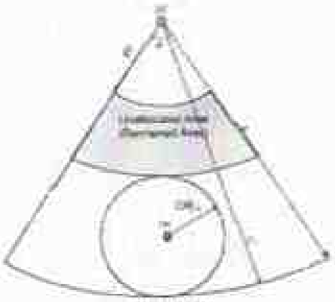

Fig. 8(d)

Figs. 8(c), (d) LND and FND. One layer is created and there exists unallocated area

The other case is called "*exceeded region*" (see Figs. 8(e) and 8(f)) in which the determined layer exceeds the network's area, i.e. $LW_1 > R - R_0$.

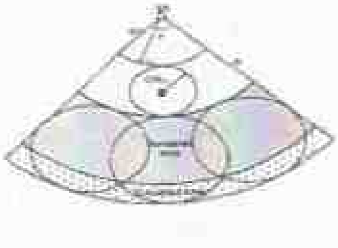

Fig. 8(e)

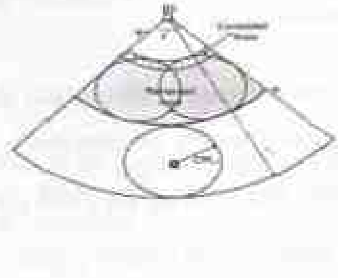

Fig. 8(f)

Figs. 8(e), (f) LND and FND. Two layers are created and there exists exceeded area

These cases are unsatisfactory and, in either case, the algorithm must restart taking a new strategy. Remember that Due to the Hot-Spot problem, layering procedure must starts from the bottom to the top in FND applications and from top to bottom in LND applications.

Case 1: Unallocated region

While LW_1 covers the whole network, the algorithm is finished. Otherwise, a part of the network may contain "unallocated region". In Figs. 8(c) and 8(d), the unallocated case is depicted for both FND and LND applications. That means one single layer is not wide enough to cover the whole network, and there must be extra layer(s). At this time, the algorithm goes on to create an extra layer in the unallocated region. Similar to above, the whole area of unallocated region is assumed as a single layer. The amount of d^2_{toBS} can be obtained from (14) for the second layer. Then, $CRL_{2\text{-}opt}$ (and consequently $LW_2 = 2CRL_{2\text{-}opt}$) is determined using derivation of (16) with respect to CRL_2. Again, it is necessary to see whether these two layers cover the whole network or not. The algorithm tries adding more layers if there is still in each iteration.

Case 2: Exceeded region

While calculating the $LW(s)$ in each iteration, it is possible that the obtained width(s) exceeds the limits of unallocated area (see Figs. 8(e), (f)). This must be avoided from the time that the algorithm starts from the first iteration by applying a constraint on layers' widths. The constraint is that:

"*AOL* obtained from Eq. (7) is smaller than the whole area of unallocated region." i.e.:

$$AOL \le \begin{cases} \frac{\theta}{2}\left[r_L^{\,2} - R_0^2\right] FND \\ \frac{\theta}{2}\left[R^2 - r_L^{\,2}\right] LND \end{cases} \tag{19}$$

by simplifying, it can be written as:

$$\begin{cases} R_0^2 - (r_L - 2CRL_L)^2 \le 0 \;\; FND \\ (r_L + 2CRL)^2 - R^2 \le 0 \;\; LND \end{cases} \tag{20}$$

where m_L is obtained from (11).

III.5.3 The Energy Consumption for Data Reporting

The main source of energy consumption is when CHs must forward the packets to the BS.

The forwarded data includes the fused packet of the CMs.

Thus each CH has to relay a single packet:

$$E^{L}_{Data\,reporting} = E_{Tx}\left(l, d^{L}_{toBS}\right) \qquad (13)$$

where d^{L}_{toBS} is the distance of CH in the L^{th} layer to BS. According to Fig. 5:

$$d^{L}_{toBS} = \begin{cases} r_L - CRL_L \; FND \\ r_L + CRL_L \; LND \end{cases} \qquad (14)$$

III.5.4 Total Nodes' Initial Energy

The total nodes' initial energy in the L^{th} layer is directly related to the number of nodes (N) in that layer that is basically related to the node density.

Thus:

$$\sum_{i=1}^{N} E_i^L = NE_{init} \qquad and \qquad N = AOL\rho$$
$$= \begin{cases} \frac{\theta}{2}\left[r_L^{\,2} - \left(r_L - 2CRL_L\right)^2\right]\rho E_{init} FND \\ \frac{\theta}{2}\left[\left(r_L + 2CRL\right)^2 - r_L^2\right]\rho E_{init} LND \end{cases} \qquad (15)$$

where the E_{init} is the initial energy of the node. Inserting (6) into (5) using ((8), (10), (14)) and simplifying, the average lifetime of L^{th} layer, LT_L is:

$$LT_L = \frac{\pi CRL_L^2 \rho E_{init}}{\begin{bmatrix} E_{Tx}\left(l', R^{L}_{Adv}\right) + E_{Tx}\left(l', CRL_L\right) + \\ m_L E_{Tx}\left(l', \frac{CRL_L}{2}\right) + \\ E_{df}\left(m_L\right) + m_L E_{Tx}\left(l, \frac{CRL_L}{2}\right) + \\ m_L E_{Rx}\left(l'\right) + E_{Tx}\left(l, d^{L}_{toBS}\right) \end{bmatrix}} \qquad (16)$$

In this equation, all terms are supposed to be a function of CRL_L, the cluster radius in the L^{th} layer. Besides, it is independent of the wedge's angle, θ, since it is omitted when simplifying.

The optimum width of each layer would be obtained via derivation of this equation with respect to the CRL_L.

III.6. Formation of the Layers

According to previous discussion, the layering starts from the furthest nodes for FND applications and closest nodes for LND applications (Fig. 7).

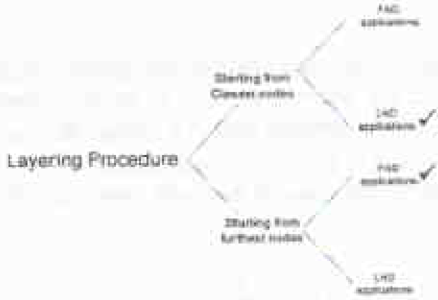

Fig. 7. Layering Procedure

The algorithm starts with a single layered network; i.e. it is assumed that initially one single layer covers the whole network.

Based on the application type (i.e. FND or LND) the exact value of d^{L}_{toBS} can be determined from (14) (see Figs 8(a) and 8(b)):

$$d^{1}_{toBS} = \begin{cases} r_1 - CRL_1 = \frac{R - R_0}{2} \; FND \\ r_1 + CRL_1 = \frac{R + R_0}{2} \; LND \end{cases} \qquad (17)$$

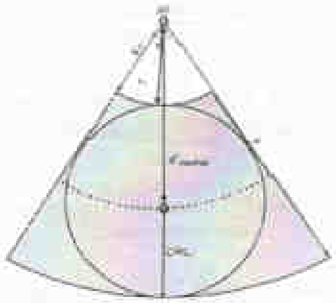

Fig. 8(a)

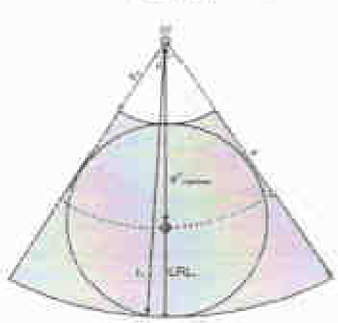

Fig. 8(b)

Figs. 8(a), (b). LND and FND: The whole network is covered with a single presumed layer

$$E^{L}_{consumption} = NoC^{L}\begin{bmatrix} E^{L}_{Cluster\ forming} + \\ E^{L}_{Data\ gathering} + E^{L}_{Data\ reporting} \end{bmatrix} \quad (6)$$

where, NoC^{L} is the number of clusters in that layer. In a wedge of the network with the angle θ, (Figs. 6), it is reasonable to assume that the number of clusters in the layer is almost equal to the "Area of the Layer", AOL, divided to the area of a single cluster with the coverage radius CRL.

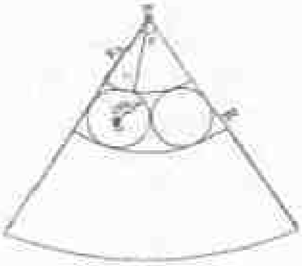

Fig. 6(a)

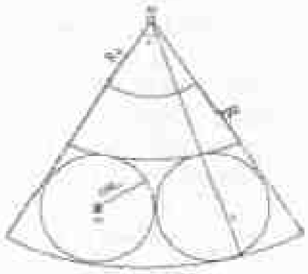

Fig. 6(b)

Figs. 6. Layers and their clusters: (a) LND, (b) FND

We have:

$$AOL = \begin{cases} \frac{\theta}{2}\left[r_L^{\,2} - r_{L-1}^{\,2}\right] & FND \\ \frac{\theta}{2}\left[r_{L+1}^{\,2} - r_L^{2}\right] & LND \end{cases} \quad (7)$$

where $\begin{cases} r_{L-1} = r_L - 2CRL_L & FND \\ r_{L+1} = r_L + 2CRL_L & LND \end{cases}$

$$NoC^{L} = \frac{AOL}{\pi CRL_L^2} \quad (8)$$

where r_L is defined as the distance between BS and external (internal) boundary of the L^{th} layer for FND (LND) and $0 \le \theta \le 2\pi$ is the angle of the wedge (see Figs. 5(a), 5(b)).

III.5.1. The Energy Consumption for Cluster Forming

The selected CHs are supposed to advertise themselves in the network so that the nodes in neighborhood choose them as their respective CHs. Each selected CH must broadcast a beacon in a radius as follow:

$$R^{L}_{Adv} = CRL_L \quad (9)$$

where the CRL_L is the coverage radius of the clusters in the L^{th} layer. More over, the nodes that heard the advertisement messages, are supposed to choose the closest advertising CH from the same layer based on the received signal strength. They send a JOIN message to the respective CH in order to be its member. If we consider a circular cluster with a radius CRL, the expected distance (mathematical mean) to the CH at the centre would be $CRL/2$. The CHs are also responsible to set a timing schedule based on TDMA for their members that is broadcasted in each cluster by the CHs. Thus, the cluster forming total energy consumption for each individual layer is modeled as:

$$E_{cluster\ formation} = \begin{bmatrix} E_{Tx}\left(l', R^{L}_{Adv}\right) \\ +E_{Tx}\left(l', CRL_L\right) \\ +m_L E_{Tx}\left(l', CRL_L/2\right) \\ +m_L E_{Rx}(l') \end{bmatrix} \quad (10)$$

where $E_{Tx}\left(l', R^{L}_{Adv}\right)$, $E_{Tx}\left(l', CRL_L\right)$ and $m_L E_{Tx}\left(l', CRL_L/2\right)$ are the energy consumption for sending l'-long messages, i.e. the advertisement message, TDMA schedule and the JOIN message respectively, while $m_L E_{Rx}(l')$ is the energy consumed by each CH for receiving the JOIN messages from the members and m_L is the number of CMs in each cluster that is proportional to the cluster's size and the node's density, ρ, (the distribution of nodes is assumed to be uniform):

$$m_L = \pi CRL_L^2 \rho \quad (11)$$

III.5.2 The Energy Consumption for Data Gathering

The amount of energy consumed by each CH for data gathering is composed of two parts. First the energy consumed for receiving data from CMs and data fusion and second, the energy consumed for transmitting packets of length of l from CMs to their respective CHs. Here we can write:

$$E_{Data\ gathering} = \begin{bmatrix} E_{df}\left(m_L\right) + \\ m_L E_{Tx}\left(l, CRL_L/2\right) \end{bmatrix} \quad (12)$$

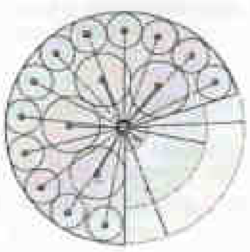

Fig. 4. A layered network

The layering algorithm is performed once in a centralized manner at the BS. The results are broadcasted through a beacon to the whole network by the BS.

III.4. Layering Criterion

In this paper, we are going to determine mathematically the width of each layer and as a result, the size of clusters within each layer using the metric, the average lifetime of that layer, which can be defined as the total nodes' initial energy divided to the whole layer's total energy consumption:

$$Average\ Lifetime\ of\ the\ Layer\left(LT_L\right)=\frac{\sum_{i=1}^{N}E_i^L}{E_{consumption}^L} \quad (5)$$

where $E_{consumption}^L$ is the total energy supposed to be consumed by N nodes in the L^{th} layer during each round and E_i^L is the initial energy of every individual node in that layer. From now on, we refer to the average lifetime of the layer by LT in this paper. Due to the Hot-Spot problem, nodes in the further layer tend to die rapidly, since they have to consume much energy for long-distance communications. Contrary, the closest nodes are supposed to live longer than others do. Based on the above statement, one can deduce that for meeting the basic requirement of the FND applications, nodes are better to be organized so that the lifetime of the furthest layer is maximized.

In contrast, for LND applications, it is required to organize nodes so that the closest nodes live as long as possible.

III.5. Calculation of Energy Consumption for Each Layer in Singlehop Communication Model

The CHs within layers are responsible for transmitting directly the packets to the sink node.
The important parameters in determining the total energy consumed in a layer are:

- Total number of clusters in each layer;
- Total number of CMs in each cluster.

In singlehop communication wireless sensor networks, further CHs tend to die much faster than closer ones due to longer distance transmission. In applications that require FND longevity, the layering procedure must starts from the bottom to the top (i.e. from furthest area to the BS to the closest) since nodes are better to be organized so that the lifetime of the furthest layer is maximized.

In contrast, in LND application, the algorithm must start layering the network from top to bottom (i.e. closest area to the BS to the furthest) since the closest nodes must live as long as possible, (see Figs. 5).

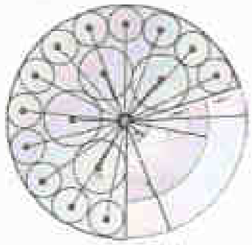

Fig. 5(a)

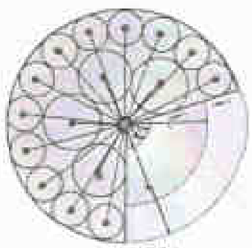

Fig. 5(b)

Figs. 5. A layered network: (a) FND application, (b) LND application

In both cases, the algorithm needs to starts with a single-layer network, so that every CH delivers a single packet to the BS. The corresponding width of that layer can be calculated. The algorithm fails if the calculated width does not cover the whole network. It has to start creating an extra layer in the remaining unallocated area and calculate the width of the second layer.

The total amount of energy consumption for each layer is needed for determining (5) that would be the sum of energy consumed by all the nodes in the layer, including CMs and CHs, in all three stages that described previously.

For each cluster, the total consumed energy is the sum of three terms:

- The energy consumption for cluster forming ($E_{cluster\ forming}^L$).
- The energy consumption for gathering all information from CMs ($E_{Data\ gathering}^L$).
- The energy consumption for data reporting to the BS ($E_{Data\ reporting}^L$).

Thus, in each round of data transmission, the total energy consumption of each layer can be formulated as:

Returning to Fig. 1, every singlehop data transmission is performed in rounds and each round is composed of three stages.

First, sensor nodes are organized into groups called clusters in a distributed manner (cluster forming).

Each cluster is composed of some cluster members (CM) and a single cluster head (CH). All CMs are supposed to send the environmental sensed data to their respective CHs periodically.

Each CH is responsible for gathering the data from the CMs (data gathering and fusion), fuses it into a single packet and forwards to the BS via singlehop communication (data reporting). Many clustering algorithms have been proposed in literatures.

In this paper, we do not deal with clustering algorithms since our main focus is on the layering approach. In the cluster forming phase the CHs are determined via a competitive time-based advertising stage, in which the candidate nodes with more residual energy tend to become CHs and advertise sooner.

For this phase, we refer to [8]. It must be noticed that in the case of singlehop communication, the furthest sensors tend to deplete their energy budget faster than others do.

In other words in direct transmission where packets are directly transmitted to the sink without any relay, the nodes located farther away from the sink have higher energy burden due to long range communication, and these nodes may die out first. To achieve balanced energy consumption, an elegant solution is to do make the clusters' size related to the energy consumption of the CHs.

Thus, smaller clusters are needed in the further distances from the BS in order to save more energy for the CHs. In the next two stages, the sensed data by CMs is gathered and fused in CHs and forwarded to the next hop that is definitely BS in singlehop communication model.

A collision free MAC layer is assumed for this stage of data transmission.

Other assumptions about the sensor nodes in the underlying network are as follows:

- Sensors nodes and the sink are all stationary after deployment.
- All nodes are homogeneous and each node is assigned a unique identifier (ID).
- Nodes are not equipped with GPS unit.
- Nodes can use power control to vary the amount of transmission power, which depends on the distance to the receiver.
- A small-scale region is considered in which the BS is directly accessible by the furthest node.

III.2. Energy Model

A simplified model shown in [9] for the radio hardware energy dissipation is used here. To transmit an *l-bit* data to a distance *d*, the radio expends:

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4 & d \geq d_0 \end{cases} \quad (1)$$

Where first term presents the energy consumption of radio dissipation, while the second presents the energy consumption for amplifying radio. Depending on the transmission distance both the free space, ε_{fs}, and the multi-path fading, ε_{mp}, channel models are used. It can also be written in a more general from as:

$$E_{Tx}(d) = p + qd^{\alpha} \quad (2)$$

In which p and q are constants related to node energy dissipation to run the radio electronics and power amplifier in transmitter and α is the path loss factor. Moreover, each CH consumes energy for receiving data from adjacent nodes or CMs and fuses it into a single packet. This consumed energy for receiving from CMs and data fusion can be outlined by:

$$E_{RF}(m,l) = mE_{Rx}(l) + E_{BF} \quad (3)$$

$$E_{Rx}(l) = lE_{elect} \quad (4)$$

where m is the number of members in the cluster, and E_{BF} is the consumed energy for beam forming data aggregation [9]. It is also assumed that the sensed information is highly correlated, thus the CH can always aggregate the data gathered from its members into a single fixed-length packet.

III.3. Problem Statement

Previous studies have shown that organizing the node into clusters will provide better energy efficiency [1]. This architecture simplifies topology management and reduces the number of sensor nodes contending for the channel access as well. The most important challenges in the field of node clustering are determining the best set of nodes as CHs and the most proper cluster sizes in the network so that the specific quality of service requirement is meet. In singlehop network, Hot-Spot problem arises when the further cluster heads to the base station excessively utilize their energy due to the distant communications; and, consequently they drain their energy rapidly. It is important to know how to perform such organization to prolong nodes' lifetime.

In this paper, we employ a method in which the network is organized into layers. The layering algorithm tends to maximize the whole average lifetime of layers.

A systematic performance study of our clustering technique is presented in addition to conducting a comparative study with state-of-the-art techniques.A layered network is depicted in Fig. 4.

clusters. The algorithm shows energy efficiency in clustering and even load distribution in the whole network. In [7] a competitive clustering algorithm is proposed that employs a time based advertising method just like [10]. Initially some of the nodes become volunteers to be CH in the network. Then they start advertising in the network using a timing schedule that is a function of energy.

Every node that has more residual energy would start advertising sooner. Each node is also assigned a competitive range that may be fixed or variable as a function of distance to BS. Every other volunteer node in its competitive range would give up if they have less energy. Otherwise, they will wait for their turn for advertising.

The authors showed that the high message overhead in CH selection phase is recovered to some extent The authors in [11] present EECS, in which the CHs are uniformly distributed across the network through a localized singlehop communication.

A competitive algorithm is suggested for CHs selection phase and a weighted cost function is introduced to manage the number of cluster members. Every node, which finds a more powerful node in its competition set, will give up the competition immediately and broadcast its QUIT acknowledgment message.

Any node that finds itself more powerful than others in its competition radius will introduce itself as a CH and broadcast its advertisement message. The message complexity in this algorithm makes trouble in the dense networks for having too many nodes competing for being CH.

A similar approach is performed in [6], in which a variable competition radius is applied to the tentative nodes.

The radius is derived from a recursive equation based on the nodes distance to the BS. Both of these competitive approaches suffer the high message overhead in CH selection phase.

In [8], a similar competitive cluster head selection approach as [11] is presented.

The proposed algorithm is named EECS-M that is a modified version to the well known protocol EECS, in which some nodes become volunteers to be CHs with an equal probability. However, EECS-M employs unequal competition ranges for tentative CH nodes.

These ranges are mathematically derived as a function of nodes' distance to BS, which makes the node to be organized into some layers according to their proximity. To find the competition ranges, EECS-M takes advantage of total energy consumption of each layer that is heuristically defined as total CHs' energy consumptions. The proposed algorithm prolongs the network lifetime rather than EECS due to more energy efficiency obtained using the unequal clusters.

Reference [12] presented a theory for maximizing the lifetime of multihop WSN.

An optimal centralized solution was presented in the form of an iteration algorithm. In [13], an investigation about cluster size and the number of cluster heads in the region was achieved when all the devices in a WSN are deployed randomly. References [14]-[15] surveyed clustering algorithms in WSN's.

III. Paper Organization

III.1. Network Model

The methodology of clustering algorithm in this paper is a hybrid scheme in which BS is the centralized authority that partitions the network into layers subject to nodes' proximity, while each individual CH takes charge of forming its own cluster in a distributed manner (Fig. 1). BS is equipped with both an enormous energy supply and a powerful radio transmitter so that is able to cover a disk of radius R centered at the sink.

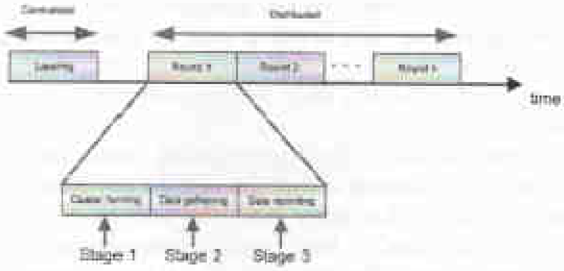

Fig. 1. The stages in the round

In the centralized phase, sensors are organized into layers around BS based on their physical distance to BS. This phase is performed once in the BS and through this the width of each layer, the upper bound (UB), lower bound (LB) and the number of layers (n) are determined mathematically (that will be discussed later) and results are broadcasted across the whole network via a "HELLO" beacon (Fig. 2).

UBn, LBn	...	UB2, LB2	UB1, LB1	n

Fig. 2. "HELLO" beacon structure

Each node in the network is able to estimate its physical distance to the BS via the signal strength received. Thus, it can determine its corresponding layer by comparing its proximity with the lower and upper bounds of the layers (see Fig. 3).

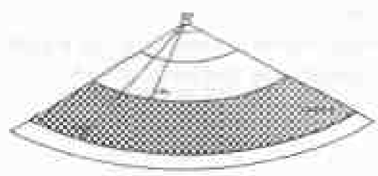

Fig. 3. Lower bound (LB) and Upper bound (UB) of layer k

further CHs to the BS have to spend much energy than the closer ones.

At this point, a Hot-Spot problem arises when these nodes excessively utilize their energy due to the distant communications and consequently drain their energy rapidly.

Expectedly, the clustering paradigm increases the burden overloads CHs, forcing them to deplete their batteries much faster than in a non-clustered network [4]. The additional energy consumption is attributed to the aggregation of intra-cluster traffic into a single stream that is transmitted by the CH; and, to the relaying of inter-cluster traffic from other CHs in multi-hop communications. Such relaying is sometimes desirable because of its power-consumption advantage over direct communication (CH-to-sink or singlehop communication).

That makes the implementation of such multi-hop networks feasible in large scale regions. In contrast, the singlehop communication networks, especially those containing homogenous nodes, are mostly applicable in small-scale regions [3].

In this paper, we consider small-scale applications that use singlehop communication for data transmission. We categorize two concepts of network lifetime that are first node dying (FND) and last node dying (LND). In FND applications, the network lifetime is considered as long as the first node dies. That means the network operation is beneficial until all nodes are alive while any node failure would make it useless.

Examples are often seen in applications monitoring crucial events and conditions such as gas monitoring in enclosed or underground car parks for not running ventilator fans all the times but when required. Another example exists in military fields where sensors are monitoring chemical activities and the lifetime of a sensor is critical for maximum field coverage [5]. In such cases any node's failure could possibly consequent a disaster. Other types of applications are the LND applications in which the network lifetime is considered as long as the last node dies. In other words, the network continues its operation until the last node is alive. In these applications, the failure of one or more nodes does not make the network useless.

An example of these applications would be humidity monitoring in greenery. Our main motivation is to introduce an analytical method to develop a hierarchical wireless sensor network that prolongs the nodes' longevity using clustering algorithms.

Innovative approach for this purpose is a Layer-Oriented clustering technique[1] (or briefly layering technique) that aims at organizing nodes into clusters in each layer subject to maximizing the lifetime of that layer which is generally considered as the main criterion. Systematically, the layering technique tends to maximize the lifetime of the first node (last node) in FND (LND) applications. The objective is to determine the optimum cluster sizes to meet the layering criterion. This is achieved by considering the width of each layer directly related to the cluster sizes and consequently the overall lifetime of that layer.

Our contributions are, on one hand, employing the layering technique in the network and derive a mathematical solution for the optimum width of each layer and, on the other hand, to provide an exhaustive comparative study that expands on our previous works in Layer-Oriented clustering approaches in [6]-[7]-[8]. Analytical methods are employed to study the impacts of both intra-cluster and singlehop communication traffic loads on the average layer's energy consumption that is formulated as an optimization problem.

The rest of this paper is organized as follows: Next, in section 2, we provide some related works that have been investigated on the same area. Section 3 describes the system specifications containing energy model, problem statement and layering algorithm. Section 4 details simulation efforts and analysis of the results obtained. Finally, section 5 concludes this paper with directions and scopes of future works.

II. Related Work

In the past few years, many clustering algorithms have been proposed for ad hoc and sensor networks aiming to improve the energy efficiency. Authors in [3] have presented a taxonomy and general classification of clustering schemes, and they surveyed different clustering algorithms for wireless sensor networks and useful comparisons are performed highlighting objectives, features, complexity, etc.

LEACH [9] is an application-specific clustering protocol that utilizes random selection and frequent rotation of CHs for distribution of the total load into all nodes. The clustering process involves only one iteration, after which a node decides whether to become a CH or not and nodes take turns in carrying the CH's role. The data communication in LEACH is based on single-hop communication model. The author also proposed two variants of LEACH, which are referred to as LEACH-C (LEACH-centralized), and LEACH-F (LEACH with Fixed clusters).

EELTC [10] is a new hierarchical clustering algorithm with multihop communication that has the ability of creating unequal clusters with very low controlling overhead. In this algorithm, a heuristic is proposed in which the network is divided into radial regions in a centralized manner based on nodes' proximity to BS. Then the BS calculates upper bound (UB) and lower bound (LB) of each layer and results are broadcasted across the network via a" hello" message.

All sensors determine their region by receiving this message from the BS. A competitive clustering phase based on region and energy is set among nodes to form

[1] Layering technique is the concept of dividing the network into regions based on a predefined criterion. (For more information see [10].)

clusters. The algorithm shows energy efficiency in clustering and even load distribution in the whole network. In [7] a competitive clustering algorithm is proposed that employs a time based advertising method just like [10]. Initially some of the nodes become volunteers to be CH in the network. Then they start advertising in the network using a timing schedule that is a function of energy.

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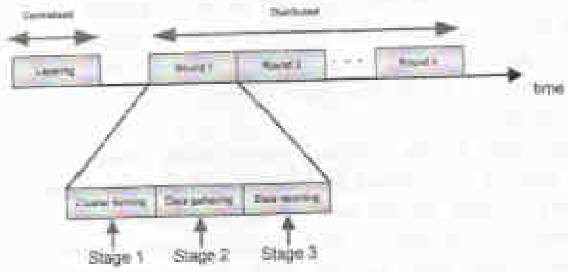

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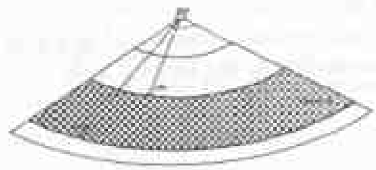

Fig. 3. Lower bound (LB) and Upper bound (UB) of layer k

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