An Overall WSN Lifetime Analysis Using Directed Diffusion and Cluster-Based Protocols

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***Abstract*—Improving the Sensor Network Lifetime through evolutionary routing protocols is one of the largest research interests. To maximize this WSN feature, the data and message delivery routes are selected in such a way that the total energy consumption is minimized. The purpose of this paper is to analyze a detailed comparison between two typical WSN protocols and their impacts over the WSN lifetime. In order to achieve to this objective, several main keys and factors such as the first dead sensor, remaining energy and transmission range are considered. The experiment results showed remarkable outcomes and confirmed that the flat and cluster-based protocols can increase WSN lifetime in different ways.**

***Index Terms*—Wireless Sensor Networks (WSNs), network lifetime, LEACH, directed diffusion, cluster-based protocols.**

I. Introduction

SELF-ORGANIZED wireless sensor networks (WSNs) are non-centralized group of the nodes that are scattered in a sensor field in order to sense an event with their particular limitation in such a way that the huge numbers of research have been developed talking about power limitations of these micro elements [1].

These battery-operated micro-devices need sufficient energy for their activities and being alive. Saving energy is one of the biggest challenges for WSNs that can affect network lifetime. This importance has been converted the lifetime as one of the focal performance metrics for WSNs. There exists enormous number of WSN applications which their main concern is: the sensor nodes can operate in a considerably large period of time without changing their batteries. The field of operation in many of these applications such as seismic activities, military, hazardous environments is inaccessible. For this reason there is a enormous effort to increase the effective operation time of whole network as well as individual nodes [2].

Up to now, there exist large amount of software and hardware based WSN developments with main objective of saving energy, and increasing the entire network lifetime. Among these approaches: Using low-power hardware element [3], [4], using low consuming WSN protocols [5], [6], node scheduling techniques [7], sensor distribution strategies [8], single-sink distribution strategies [9], using effective MAC [10], are some samples of these advances. The main idea in all cited cases is to reduce the power consumption and saving energy in order to increase the stable time of operation for each single node. There exist many studies that directly deal with the lifetime of the global WSN system that will be discussed in the following section.

As said in all mentioned cases, there is a big concern of increasing the global network lifetime. Many of them are concentrated on improving the routing protocols to prolong the network lifetime. This research explores the single-sink WSN flat [9] and clustered scenarios by using two classic types of WSN routing protocol: Directed Diffusion that is a flat data-centric protocol and LEACH that is a cluster-based protocol. The experiments are designed and simulated using predefined sensor deployment strategies.

Actual work takes into consideration the lifetime as the main performance metric of a flat and clustered WSN.

The main key in this research is to study the performance evaluation of a WSN in terms of the global and per node lifetime. The performance evaluation, in this study, is evaluated under the flat query cycle and cluster-based experimentations in the predefined deterministic and non-deterministic environments.

The focal point in this paper is concentrating on the particular features that determine lifetime of a node o whole system such as: sensor death rate, first dead sensor, total dead sensor, total remaining and consumption energy and consumption per cycle in both flat and hierarchical WSN structure. It is a single-sink routing-based approach that compares efficiency of sensor network based on the mentioned features.

Organization of this paper is as follows: firstly, a comprehensive explanation associated to Directed Diffusion (DD) and proposed cluster-based routing protocol is presented. Then, a system model and its components along with a detailed description of system setting are outlined. After that, a statistical analysis of achieved results will be presented. And finally, last section introduces some conclusions and suggestions for future works.

In order to have a clear idea about this research a short survey on the flat and hierarchical WSN architecture is discussed in the following section:

A. Flat Architecture

Flat wireless sensor network architecture is a homogenous system that all sensor nodes are equal in their roles that they perform. A dense amount of micro nodes which are identical in battery capacity, initial energy, and main hardware characteristics such as radio transmission range and communication pattern are grouped and formed a flat WSN infrastructure.

In this type of structure, base station node (sink) has a different role from other nodes which can be a static or a mobile node. The network includes the simple member nodes that operate like a router. They administrate flooding

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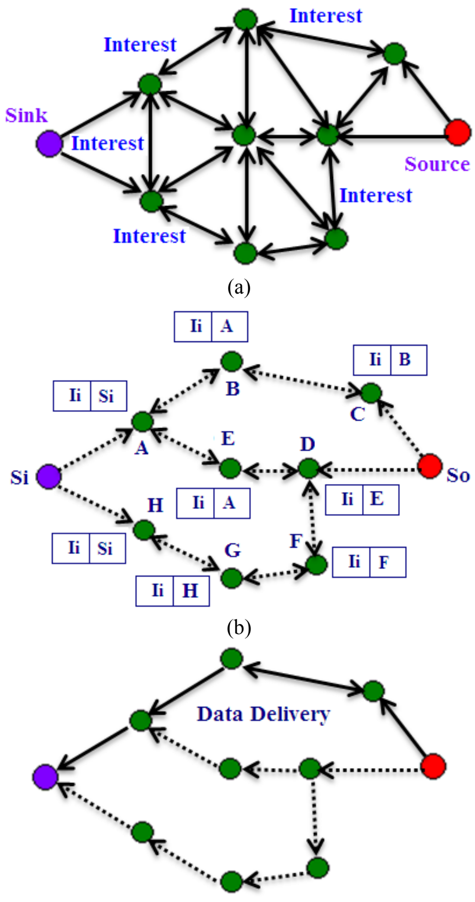

Fig. 1. (a) Interest propagation, (b) gradient setup phase, and (c) data delivery phase.

and sensing process, deliver sensory data through multi-hop routing and finally relay data to a remote base station in a flat infrastructure [11], [12].

Flat sensors participate in the message propagation over the network and transfer data to the sink in the phase of data delivery, using a data-centric routing algorithm scheme such as Directed Diffusion [13].

Directed Diffusion (DD) is a flat protocol developed by Chalermek *et al.* DD is a data-centric and application-aware protocol in a diffusion-based network that by choosing shortest paths, caching and local processing data to achieve energy saving. Data generated by sensor nodes is labeled by attribute-value pairs. A particular node requests data by sending interest message for named data. Data request matching the interest is then drawn towards the sender node. Relay sensors can store or transmit data based on previously collected data [13].

DD consists of some principal processing elements. They are: Naming, Interests and Gradients, Data Propagation and Reinforcement. An attribute-value pairs is used for naming data. In the sensing search phase an interest message or a query is broadcast on the whole WSN for named data. As the message is spread over the network the gradients are set up and when a data matching interest occurs, the sources sending back the sensory data along multiple paths. Finally sensor network reinforces one of this pathways or small number of them [14]. These components are shown in Fig. 1.

As Fig. 1 shows, an interest message is periodically broadcast over the WSN (flooding). When a node receives

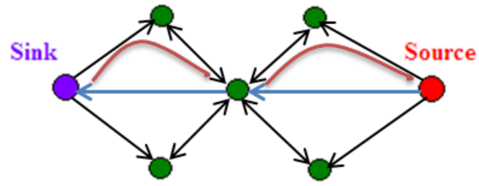

Fig. 2. Reinforcement in directed diffusion.

an interest packet, it checks to see if the interest exists in the cache for possible matching test. A gradient specifies a value and a direction (path) that contains the information about neighbors defining the direction where to send data messages. In data propagation phase, data which named by attribute-value pairs and represent the event sensory data compare to the request in order to examine matching interest entry. If a match exists, the node checks the data cache to find the match interest message entry. And if no match exists, the data message is dropped [13].

Once source node discovers a matching target, it sends the low-rate events along multiple pathways to the gateway. On receipt of low data rate events, the base station reinforces the preferred neighbors which, in turn reinforces its preferred previous-hop node in order to "draw down" real data by means of data driven local rules. Fig. 2 illustrated reinforcement details.

Reinforcement is the main difference element between two variants of the Directed Diffusion protocol; One-phase & Two-phases pull versions, that this dissimilarity is discussed in the following.

One-phase pull is a subscriber-based protocol that excludes one of two phases of flooding present in two-phase pull. Unlike two-phase pull, when a request message reaches at a node source it does not mark its first data message as exploratory, but instead sends data only on the preferred gradient. One-phase pull DD assumes symmetric communication between sensor nodes since the data path (source-to-sink) is determined by lowest delay query path (sink-to-source). While in two-phase pull DD, selection of data path is decided by the lowest-latency exploratory messages, both in the source-to-sink and sink-to-source directions. This reduces the disadvantages of symmetric communication in one-phase pull DD [15].

Also, one-phase pull uses a flow-id that it makes interest size grow with number of sinks. But in Two-phase pull, the number of interest messages raises with proportion to the number of sinks, so the cost here is lower [13]. By comparison, it can be found unlike Two-phase DD, One-phase version of DD theoretically can be a suitable flat routing protocol in the single-sink or single-source WSN scenarios.

B. Clustered Architecture (Hierarchical Topology)

Opposed to the flat architecture, in a hierarchical environment, sensor nodes perform different jobs in WSNs and are grouped into many clusters according to particular requirements based on the power level and proximity. The clustering process leads to a hierarchy of clusters. This process called "Hierarchical Clustering" [16]. Fig. 3 illustrates a typical hierarchical structure.

One of typical clustering routing protocols in WSNs is LEACH (Low-Energy Adaptive Clustering Hierarchy) that has been an inspiration for many hierarchical WSN

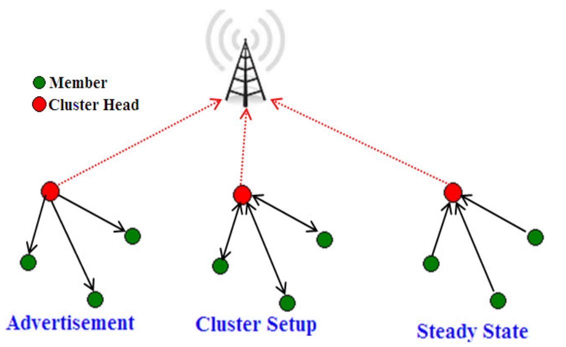

Fig. 3. Round based operation of LEACH.

protocols [17]. Also, there are some other hierarchical clustering protocols that have been individually developed. However, all cluster-based experiments in this paper are based on the LEACH. Usually, each cluster includes a leader refer to as cluster head (CH) and other sensors of the cluster are regular nodes. CHs perform data processing and transmission functions while regular cluster members act as the sensing nodes. The main idea applied in designing of LEACH is the sensor node clustering is based on the on the received signal strength and use local cluster heads as routers to the sink. Involving the sensor nodes in a particular cluster theoretically is an effective strategy to perform data aggregation and fusion tasks in order to decrease the number of transmitted messages to the sink in order to reserve energy within the cluster. Data fusion and aggregation processes are local to the cluster. Cluster heads exchange their roles randomly over time in order to balance the energy dissipation of nodes. A sensor node converts to a CH for the current round if the number (random number between 0 and 1) is less than the following threshold [5]

$$T(n) = \begin{cases} \dfrac{P}{1 - P \times r \bmod \dfrac{1}{P}} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where P is desired percentage of cluster heads, r is current round, and G is set of nodes (not been cluster heads in the last $1/P$ rounds).

Regular sensors, after receiving the advertisement from a single or based on the signal strength of the advertisement from the multiple CHs determine the cluster that they will belong to. This is called set up phase. After building the clusters, LEACH initiates a steady state phase. The cluster members start sensing and transmitting sensor data to the CHs. At the end of this phase, the system goes back to the setup phase again to start another round of CH selection. Round-based CHs selection is considered as an effective energy consumption balancing approach due to distribution of the energy dissipation between the whole systems. On the other side, within steady state phase, just CHs are active regularly while the cluster members are active only during the setup phase and its assigned time slot [18]. Fig. 3 illustrates the round based operation of LEACH in a typical clustered WSN.

In the hierarchical clustering architectures, the sensor nodes die randomly and dynamic clustering improves global network lifetime. LEACH is entirely distributed and doesn't need a global knowledge of the system. It uses single-hop routing and each node can communicate directly to the cluster-head and the base station. Consequently, it is not applicable to the large scale wireless sensor networks [19].

After explaining theoretical components of the research, a system model that provides a comprehensive scheme of WSN configuration is presented. It is included the experiment layout scenario, deployment topology, energy and radio transmission models and other details related to the system that will be discussed in following.

II. System Model

A. Sensor Node Placement Strategies

Random and deterministic sensor deployments are considered as two distribution strategies.

A non-Gaussian random deployment is considered in this work as defined in [20]: where N is the total number of sensor nodes deployed in the field with area A. Node density of N sensors is defined in (2) as: ρ is the total density

$$\rho = \frac{N}{A} \quad (2)$$

Based on [20], the probability that K nodes are positioned inside its communication range R, for each node is defined by next equations: p is defined as the probability of falling two sensor nodes inside their respective communication radius

$$p(k) = \binom{N-1}{k} p(1-p)^{N-1-k} \quad (3)$$

$$p = \frac{\pi R^2}{A} = \frac{\pi R^2 \rho}{N} \quad (4)$$

Another popular deployment strategy is deterministic uniform deployment of the sensor nodes. It is a general purpose distribution in which the sensors are located in each row within equal distances.

In this strategy of placement all sensor nodes are placed in the equal distance creating a homogeneous type of wireless sensor network.

B. Query Cycle

1) Query Cycle in the Flat Scenario

Once a request message is broadcast over the WSN and an answer matching is detected the answer is routed to the base station. If an interest message is flooded and successfully received by sink within a propagation time that includes broadcast in addition to data delivery time. It will be considered as a Successful Query (SQ) and this round is defined as a Query Cycle (QC). Unsuccessful queries can take place when the sink doesn't receive any answer during a finite interval propagation time. This time is not calculated as a valid QC.

2) Query Cycle in the Clustered Scenario

As the base station injects a request, if there is any sensory data for reporting from any CHs of the system, they receive the data and send back to the base station. The procedure of sending and receiving the messages between leader, regular sensors and the base station is defined as a Query cycle. The sensors can die as they do not have

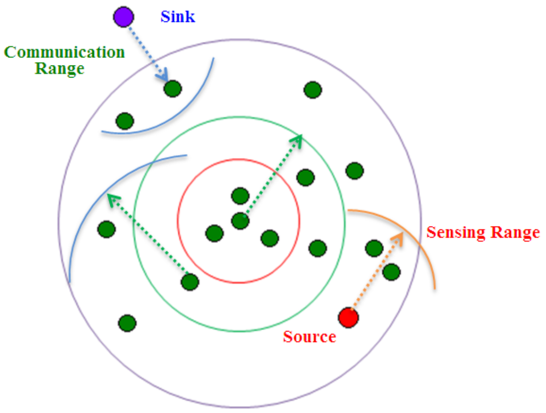

Fig. 4. Communication and sensing radius of a WSN.

sufficient energy to receive or transmit the data or control message in different query cycle.

C. Radio Transmission Range of a Sensor Node

One of the physical configurations that can affect the energy consumed by each node and logically total energy consumption of entire network is radio transmission range of the sensors. Finding an optimal transmission range which minimizes the effective energy consumption by each node and extend network lifetime is the focal point of many researchers [21]-[23]. Radio transmission or communication range is a special hardware feature of a mote and can be varied for each sensor based on their electronic and RF elements.

In this research MICAz which is a family of MICA mote [24] is considered as the sensor node used in the experimentation. Based on the technical characteristics of the "mote" the outdoor communication range of this sensor is 75-100 m at a rate of 250 kb/s. Fig. 4 exhibits a typical scenario of a WSN with the corresponding radio communication and sensing radius.

Fig. 4 illustrates a typical WSN topology. There exist three kinds of actor. The base station is considered as the Sink. The routing sensor nodes and source node that is determined with a red color. One assumption in this study is radio communication range of the Sink and routing nodes are not equal to sensing range.

D. Network Lifetime

In this work, the focal of WSN performance metric evaluation is network lifetime. Lifetime is one of the main measurement keys to estimate the stable period of time in which the network is operational while network structure is dynamically changing to compensate tasks of dead sensors. Sensors are battery limited and can die.

Sensor death can generate disconnected small areas in the field that can cause a total or partial disconnection between base station and source nodes. This situation can shut down the whole system. For this reason prolonging of this period is of essential interest.

As previously discussed, the network lifetime is defined based on the time that sensors start dying (critical point). However, in a practical network lifetime analysis, since sensor networks are self-organized they can restructure their map dynamically.

In order to measure utilization efficiency of sensor nodes and also, estimate the increasing rate of network lifetime

TABLE I
WSN ENERGY CONSUMPTION FEATURES

$Ecpu_{Data}$	100 µJ/message
$Ecpu_{Signal}$	3.2 µJ/message
Esensing	66 µJ/s
ETx_{Data}	$(100+200xd^2)$ µJ
ETx_{Signal}	$(13+64xd^2)$ µJ
ERx_{Data}	100 µJ/message
ERx_{Signal}	3.2 µJ/message
E_{idle}	40 µJ/bit

with total initial number of nodes, Y. Chen *et al.* [25] defined the network lifetime per unit cost as follows

$$\frac{E(L)}{N} \tag{5}$$

Network lifetime $E(L)$ divided by the number of sensors deployed in the network is defined as lifetime unit per cost. With a minor difference, network lifetime per unit cost in this work (equation (6)) is defined to compute the rate
at which network lifetime growths with number of alive nodes N_a

$$\frac{E(L)}{N_a} \tag{6}$$

E. Energy Consumption Measurement Model

Each node requires enough energy for its survival and being an active part of a self-organized network while power failure of the nodes can interrupt and shutdown the system.

In order to save energy each node should work in active mode (wake up mode) at the shortest period of the time. The total energy consumed by sensors is computable based on the first order radio model [26].

Equation (7) illustrate the energy dissipated for sending or receiving a m-bit message to/from a distance d can be calculated as follows [26]

$$Er = ERx + ETx \tag{7}$$

where ERx and ETx are the energy consumed to receive data and control messages, respectively.

The minimum energy dissipated by electronic sensor is calculated as follows

$$E_{board} = Er + Ecp_{Signal} + Ecp_{Data} + Esen \tag{8}$$

Equation (8) is calculated considering following assumptions for MICAz mote:

- Data rate = 250 Kbits/s.
- Communication Range R is higher than the sensing range and fixing on $R = 87\,\text{m}$.
- Sensing range for source $so = 50\,\text{m}$.
- The Data and control message size are fixed to 2000 bits and 64 bits, respectively.

The RF transceiver is an IEEE 802.15.4 low-voltage and low-power that contains a DSSS baseband modem. It can run spreading gain of 9 dB with a data rate of 250 kbps. The RF channel can be adjusted within the IEEE 802.15.4 channels from 2.405-2.480 GHz. The radio transmission power is adjustable from 0 to -25 dBm [24].

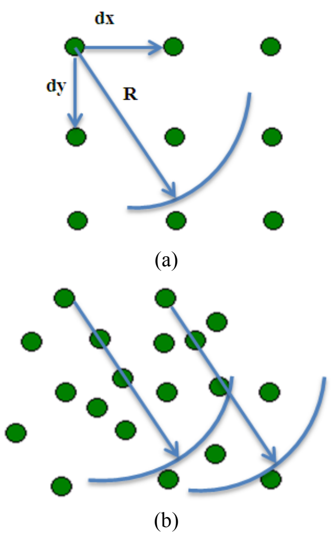

Fig. 5. (a) Deterministic topology and (b) non-deterministic topology.

Based on the [19], it is assumed that the radio dissipates at 50 nJ to run the transmitter/receiver electronic-circuit board and at 100 pJ/bit/m^2 for the transmit amplifier [19]. Table I summarizes WSN energy consumption features by each node.

Based on the predefined parameters in the Table I, the process of the data reception is an expensive operation.

A useful assumption in this study is considering a symmetric radio channel to balance the transmitting energy in both side of the communication. Another assumption is all sensors nodes operate at a fixed rate of sensing in such a way they always have sensory data to send to the base station [19].

F. Time Delay Measurement Model

WSN delay is determined by several sensor network parameters such as node schedule activities, environment density, routing patterns, geometric factor of sensor allocation, type of application and transmission range. It is the metric that describe how fast the incident can be detected, processed (locally) and reported.

In this work, end-to-end time delay of a message is the time it takes "Data" to reach at the endpoint after leaving the sink and get back to the starting point.

End-to-end time delay in this study is defined as the period of time that it takes to inject an interest message and receive the corresponding answer [27].

In one-phase DD algorithm, a small fixed-length packet is propagated over the network and a data response packet will be back over the shortest route. Two specified transmission delays are supposed in the whole process: Message and data transmission delay between two hops. As the propagation and processing times are very small and negligible against the transmission time, the transmission delay between hops is the dominated time assuming there is no queuing. Based on the previous assumptions and selected parameters of the radio model calculation, the message transmission time delay amount between two nodes will be 256 µs of time and delivering data between two nodes takes 8 ms of time [27]-[29].

End to end time delay is computable in cases in which the queries are successful, otherwise the query is declared unreachable. The experiments are repeated and a round-trip time delay per query is calculated for each SQ, taking into consideration the message transmission time in the broadcasting phase and data transmission time when an answer arrives to the sink.

Per-query time delay can be obtained by dividing the total time by SQ.

G. Deployment Topology

The sensor nodes are positioned in two deterministic (uniform) and non-deterministic forms as shown as in Fig. 5.

They are deployed in two scenario of $N = 100$ and $N > 100$ nodes as the low and high density distributions, respectively.

In a typical experiment scenario, the base station injects a request into the network and the message is broadcast over the whole WSN by using One-phase DD. All sensor nodes with sufficient energy receive and resend the query to their neighbor nodes. The sensor nodes that are located inside of the sender transmission range (neighbors) receive the query, consume some energy and resend it to their neighbors. This process is repeated until all nodes receive the interest message. When a query match occurs, the source node transmits the sensory data back to the base station. An accomplished query is called as the SQ. All wireless components in a SQ consume energy in the flooding and in data delivery process.

As said, the total energy consumption of a SQ is calculated besides the total SQ in the process until broken of all established links between sink and source/event. This happens due to death of those sensors which wasted their energy and also, in the situations in which there is no alive sensors located within the source node communication radius to communicate to the sink. In case of end-to-end time delay variable, the hop by hop transmission time delay is calculated in a SQ. Finally, an average value of energy consumption and time delay per query is calculated as the performance metrics of the network [8].

In both cases, all experiments have been done in different communication radius of the MICA sensor. It is considered that the radio transmission range of all nodes is the same and adjustable. Based on the physical characteristics of MICA sensor, this device operates in an outdoor range of 75-100 m.

The experiments are implemented in various theoretical transmission operating ranges of 55-100 m that are controlled by different power transmission levels. It is required to note that the power transmission level is not a focal point in this research.

All WSN devices are set to the same amount of communication radius in each experiment. For each group of the experiments a particular transmission radius is set to the nodes. The transmission values are selected from the operational transmission range of the MICA sensor. These values are grouped in a 10-element collection. As each experiment is executed, one number is selected and fixed for all RF devices. This action is repeated for all elements. And finally, for each number of radio transmission, the average energy consumption is measured only for SQ.

Following section describes the results obtained from experiments along with their related analysis.

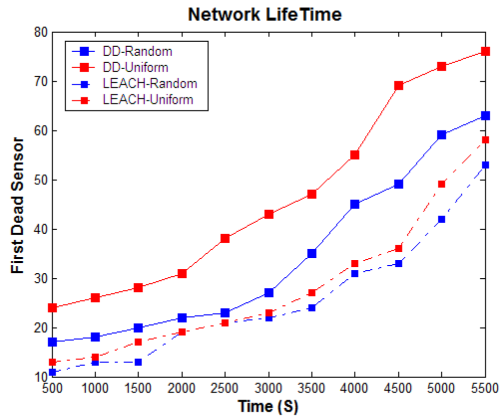

Fig. 6. WSN lifetime in deterministic and non-deterministic topology.

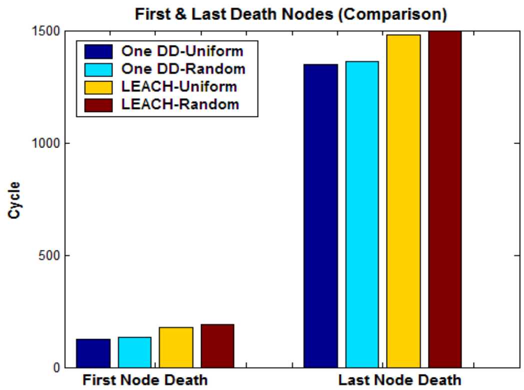

Fig. 7. First and last death of the nodes.

III. Results

A cumulative result of the whole experiments is presented in this section. Firstly, the result related to the network lifetime in terms of first dead sensor nodes are shown in Figs. 6 and 7, as follows.

For starting, Fig. 6 illustrates the first sensor death that occur in different period of WSN lifetime in two flat and hierarchical structure using One DD and LEACH protocols, respectively.

Fig. 6 depicts behavior of the system based on the first dead sensor node or stress critical point. In the critical point, the first sensor nodes start dying and are taken out of the whole WSN scheme. In some situations, absence of the nodes can generate an energy hole problem in some areas. As Fig. 7 shows, there is a significant difference in lifetime behavior between two protocols and strategies. As both Figures demonstrate, LEACH demonstrates a better lifetime performance in terms of the first dead and last sensor nodes death. One DD has a high level of first dead sensors when sensor nodes are deployed in a random non-deterministic environment comparing to others.

A lower number of sensors are dead in case of LEACH random and uniform cases vs. One DD flat case. Fig. 7 also shows, the rate of sensor death which growth over time. Based on the results obtained from experiments LEACH beats Directed Diffusion protocol in the node death rate and produces the better network lifetime. This preference in the first 500 s life of the network is almost 65% better than the One DD which this difference can reach to an almost 80% in the last time of the network life time.

Based on the Fig. 8, the stability state of the network in

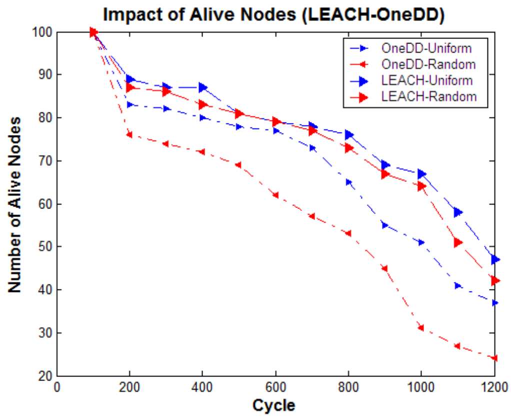

Fig. 8. Impact of alive nodes in different cycle of operation.

the normal condition where none of sensor nodes die in case of LEACH is longer than the One-phase Directed Diffusion protocol.

Fig. 8 also shows the difference between the One DD and random LEACH in terms of the first dead and last sensor death is 25 and 10%, respectively. However, Figs. 6 and 7 confirm that using a clustering sensor node placement strategy can improve the network lifetime in terms of the first sensor death. A supportive result that analyzed number of alive nodes in different cycle life of the WSN is presented in Fig. 8.

According to the results, the critical cycle number is 120^{th} cycle. But the first drastically sensor death happens in the cycle number of 200 in which the first higher number of nodes start dying. This event continues with a fixed slop in all cases.

However, LEACH uniform and random cases has a reasonable behavior regards to sensor death rate. The worst case belongs to the One-DD random case that with rather sharp changes in slope goes down while these changes in LEACH is slightly smooth.

In summary, the results confirm that the higher number of sensor can survive when they are grouped in a small clusters and report to their cluster head compare to the situations in which all of them are identical in their role in routing and delivering Data to the base station. This fact is shown very clear in Fig. 8.

The results related to energy consumption per cycle and per node, in addition to details of the remaining energy in terms of deployed sensor nodes are presented in Figs. 9-11, respectively. Fig. 9 depicts the energy consumed in each cycle in a predefined period of cycle number 100 to cycle number of 1000. As Fig. 9 shows, despite of consuming amount of energy by One-DD and LEACH there is a break point at cycle number of 700, the speed of energy consumption per cycle increases radically in all cases. This is because of high sensor death rate and lack of sensors in some areas that generates several energy hole issues in which other coordinating sensor nodes try to compensate the absence of the nodes and their tasks in the field.

In general, the behavior of the system in terms of spending energy in each cycle is similar for all protocols, but using One-DD guarantees less energy consumption in one cycle vs. LEACH and Two-DD. LEACH follows a reasonable pattern of energy consumption comparing to the complete version of Directed Diffusion that uses

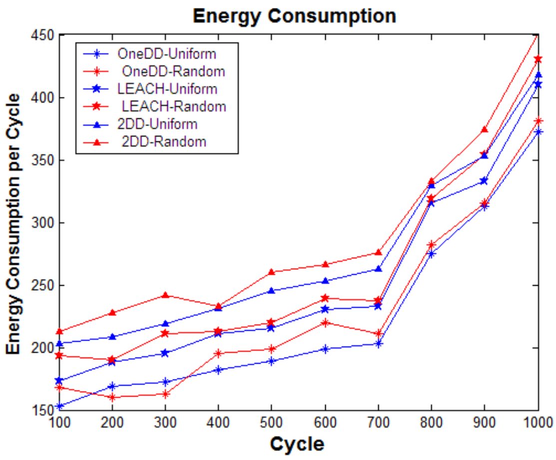

Fig. 9. Energy consumption in different cycle of operation.

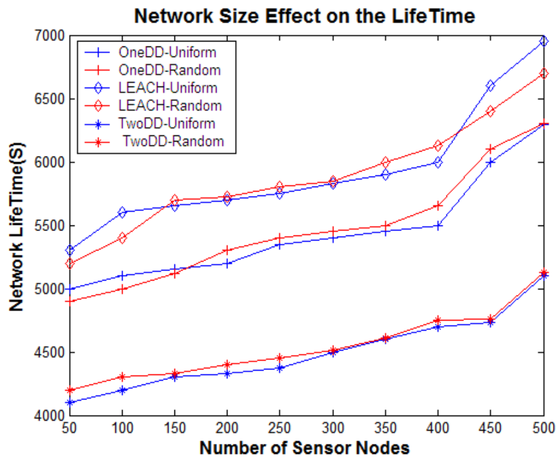

Fig. 11. Network size effect on the WSN lifetime.

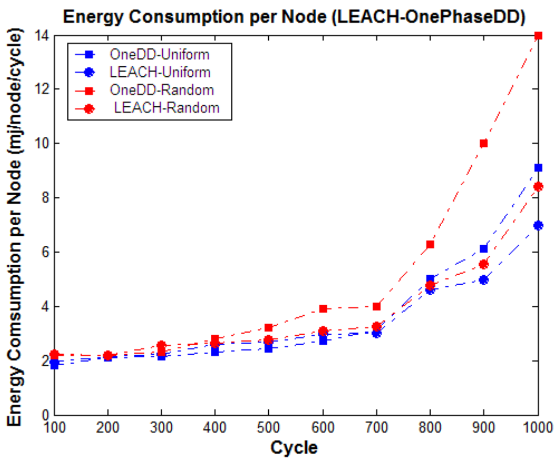

Fig. 10. Energy consumption per node in different cycle of operation.

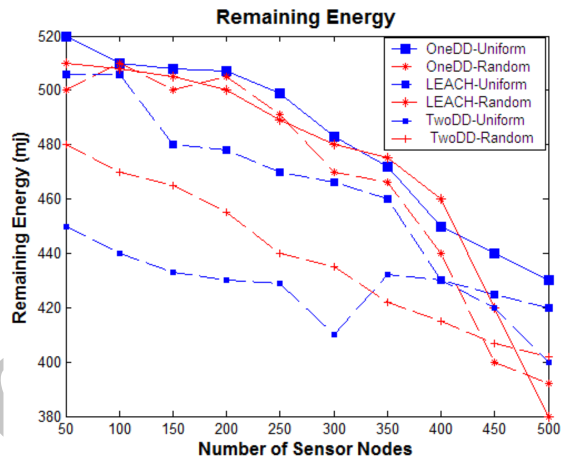

Fig. 12. Total remaining energy in different size of network.

reinforcement process that it means implicitly more energy consumption in Data routing process by coordinating nodes.

Another useful energy consumption analysis is associated to comparison of per node power consumption in one cycle. As Fig. 10 demonstrates, in the first cycles of the network operation in both flat DD protocols and LEACH almost all nodes consumes in the same level of energy with a 5% fluctuations. This situation continues up to 700^{th} cycle. After this stability period each protocol runs differently, in such a way that in a flat scenario of the sensor nodes which are deployed randomly, the sensor nodes drives more energy than the clustered scenarios in the next cycle of their lives. Uniformly grouping the nodes makes a balance in the energy that consumed by the cluster members in their cycles of the operations.

Remaining of the energy in the system could be another key metrics in the lifetime analysis for sensor networks. Fig. 12, represents the results related to this factor. But before analyzing Fig. 12, let's check the effect of sensor density in terms of the network size on the network lifetime. Consuming large amount of energy in the weighted process causes power deficiency in the whole network. This fact is clarified in Fig. 11 indirectly. Hence, the real competition is between One-DD and LEACH.

Based on the result obtained in the experiments, in all sensor densities' categories, One-DD beats clustering approaches. This could happen because of effective balancing mechanism for energy consumption and large number of alternatives routes in the field while sensor nodes are positioned uniformly. When sensor nodes are distributed in the non-deterministic schemes what could be happened is unpredictable. However, because of the self-organizing characteristic of WSN they operate as a non-centralize network, properly. Consuming of energy, routing administration and Data delivery processes is managed by the applied algorithm. In this case (low scale of density, $N < 100$ nodes), the results of the task executions in both cases of LEACH and One-DD is very similar as shown in Fig. 11.

The situation in the large scale and high sensor density is different from the lower density cases. Huge number of nodes is deployed in a small area. They are more densely packed and therefore broadcasts reach many more sensors, accordingly use much more energy and power usage increases at a higher proportion than the increment in the number of nodes. On the whole, because of involving more sensor nodes in the operation higher level of energy is consumed in the situations in which huge number of nodes closely positioned in the field. Fig. 11 illustrates this effect on the network lifetime which LEACH shows a significant preference over Directed Diffusion protocol and its variants.

Coming back to Fig. 12, it is plotting the total remaining energy of the WSN in different sensor node densities from a low scale to a large scale of deploying of the nodes. As expected theoretically, Two-DD implements a heaviness algorithm that ends to perform more activities concluding

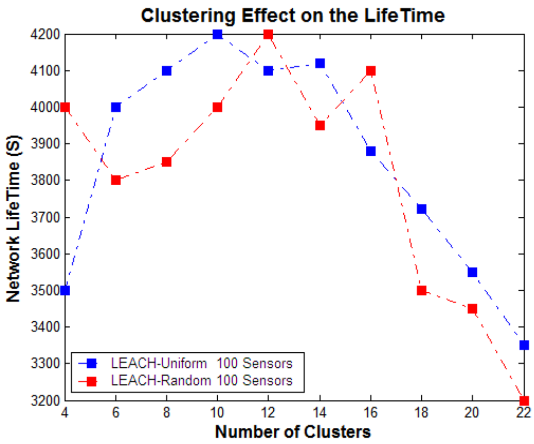

Fig. 13. Clustering effect on the network lifetime.

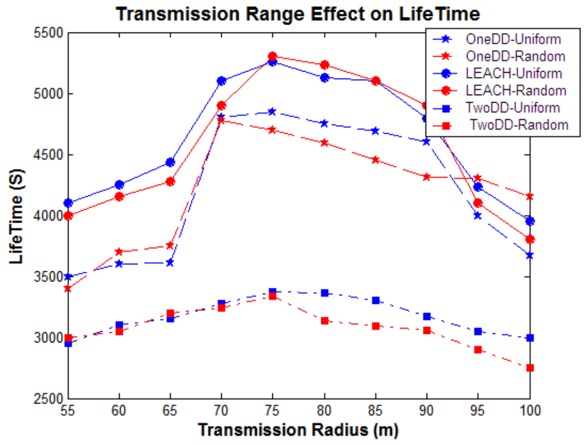

Fig. 14. Clustering effect on the network lifetime. (ba 13 yekist)

higher amount of energy consumption by assigning more activities for nodes in the routing and Data delivery process.

An energy remaining comparison between LEACH and One-DD demonstrates that in a high sensor density, One-DD wins against LEACH in terms of power that consumed by whole alive sensor nodes in the network. It could mean One-DD administrates total energy that exists in the WSN better than the LEACH. This reality that confirms *saving energy* in a flat WSN which utilizes One-DD algorithm is succeeded much better than using clustering approaches is shown in Fig. 12.

As shown previously, clustering approach can prolong the network lifetime. Other helpful results related to the clustering and its relationship with network lifetime is presented by Fig. 13. The results depicted in Fig. 13 are belonging to a particular simulated case study. 100 sensor nodes are scattered in two strategies of deployment. The nodes are placed uniformly in 10 rows within uniform distance. Another distribution strategy that applied in this case study was deploying sensor nodes in a non-deterministic randomly way which is the most popular strategy of sensor positioning.

Fig. 13 illustrates the results obtained from experiments in a variable clustering approach and their corresponding network lifetime. Based on this result, this particular uniformly scattering of the nodes has a rational impact over whole network lifetime. However, the most crucial reality observed in this experiment is number of clusters and their influence on extending the network lifetime. As Fig. 13

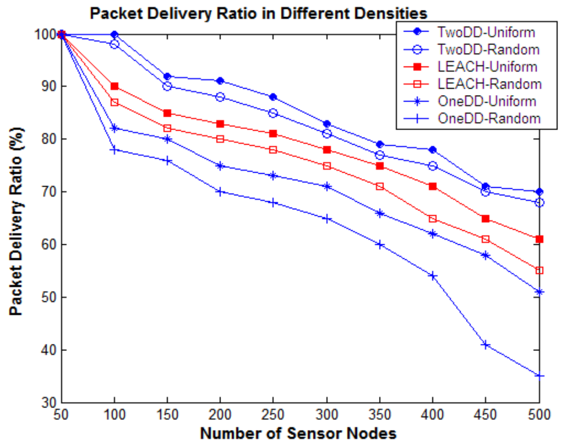

Fig. 15. Packet delivery ratio in various sensor densities.

shows, almost in both cases, there is an optimal range for number of clusters regards to the lifetime performance.

It can be observed: small number of sensor groups and very large numbers of sensor node clusters cannot promise prolonging entire network lifetime.

Radio transmission range and its effect on extending stable operation lifetime of a WSN is another studied factor in this research. Results related to this factor are figured in the following.

Fig. 14, depicts simulation results associated to influence of radio transmission radius on the WSN lifetime. The results are remarkable. As well as clustering effect that was explained in the previous section, there is an optimal range in which lifetime performance of WSN is higher than other segments.

According to the results, Two-phase Directed Diffusion protocol is out of the competition while it shows a similar pattern to one-DD and LEACH in a lower level of effectiveness.

One-DD and LEACH have a very close lifetime performance behavior in different range of sensor node communication radius, but in a varied levels. Both LEACH and One-DD show an optimal performance in a communication middle range of 70 to 90 m. The transmission radius out of middle range (lower than 70 & higher than 90 m) demonstrates lower significant impact on prolonging the WSN lifetime. However, LEACH is the one wins vs. One-DD in respect of the lifetime performance.

Because of flat nature of Directed Diffusion protocol, and creating large amount of routes and alternative paths relatively, the shortest routes are selected. Carrying the small size of packets across these shortest routes significantly decreases rate of power consumption by nodes and as a results ends to improving network lifetime comparing to the case in which more weighted message are transferred through network. Results also confirm that the process of energy balancing using small size of the messages in the flat protocols is performed much better than the cluster-based types where CHs assume this role and there is no any energy hole in the system.

In order to compare the behavior of LEACH and Directed Diffusion protocols in terms of the packet delivery ratio, Fig. 15 plots this feature showing a rather sharp reduction when the number of sensor nodes rises above 100.

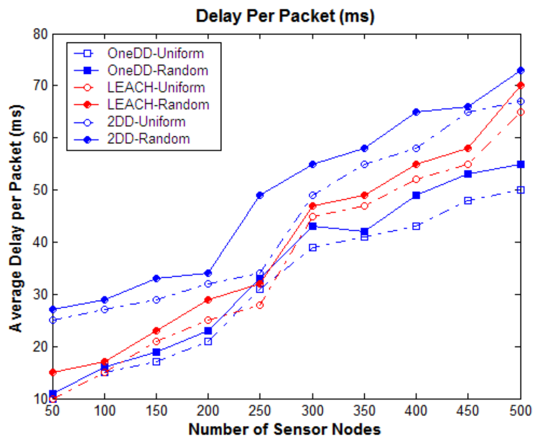

Fig. 16. Average delay per packet.

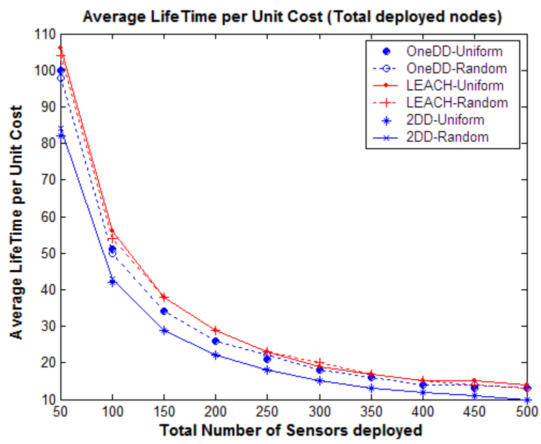

Fig. 18. Average lifetime per unit cost.

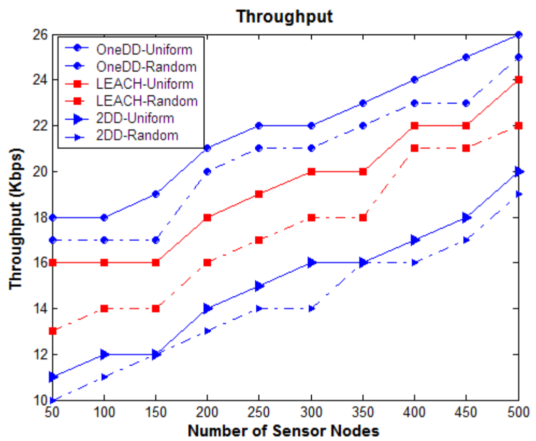

Fig. 17. Throughput in various sensor densities.

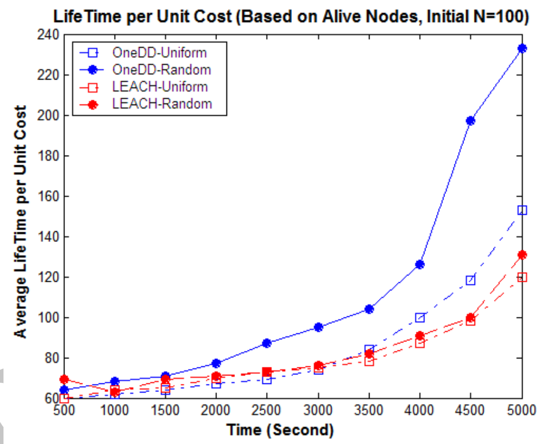

Fig. 19. Average lifetime per unit cost as function of time (s).

This descent occurs for all cases because the high congestion of routing overhead around nodes than can obligate packets to be dropped. Fig. 15 depicts the results related to the average rate of successful data delivery over a sensor network in various density of nodes. Also, the average delay that the packets are experienced in these situations are measured which are presented in Fig. 16.

According to Fig. 16, LEACH demonstrates a rational action against Directed Diffusion protocol. As was expected, the average time delay for Data/message in Two-DD because of having long routes and reinforcement process is higher than the One-DD and LEACH. Clustering the nodes can help to shorten the route length. The nodes just report to the CHs, communications are limited between member nodes to CHs and CHs to the base station or to Gateway nodes. One-DD can create more efficient routes and also provide paths that are much closer to the optimal direct path, while it is impossible for LEACH. However, in One-DD the packets are delivered in the small slice of the time, as a result the average time delay per packets in this protocol are less than the LEACH. As was expected and simulation results confirmed, One-DD demonstrates better response in terms of this factor vs. other protocols.

Fig. 17 shows the results of the throughput as a function of the sensor node density. Throughput is measured by the number of packets received per second at the sink node. In this study the number of sensor nodes are varied from 50 to 500 and throughput is measured at the base station. As Fig. 18 shows, it can be observed that by increasing the number of nodes, the throughput for One-DD, LEACH and two-DD increases at a rather monotonous rate. In a large scale size of WSN One-DD has achieved higher level of throughput than the LEACH and One-DD.

The result confirmed that the One-DD protocol is scalable as the size of the WSN becomes larger. Out of two evaluated protocols, One-DD has the best throughput, while LEACH demonstrates a reasonable scalability, efficient performance and better than other variant of the Directed Diffusion that is called Two-DD.

Lifetime per unit cost is one of the most effective method to evaluate the WSN lifetime in terms of the alive nodes. Figs. 18 and 19 illustrate the result associated to this factor as function of total sensor node density, alive sensor nodes and execution time.

Based on the results presented there is a direct relationship between total number of initial deployed sensor nodes and lifetime per unit cost. It is very clear this fact that as number of sensor nodes (large scale WSN) increases, average lifetime per unit cost decreases exponentially. Fig. 18 plots this feature showing a very sharp reduction when the number of sensor nodes in the network rises above 100 (50% falling).

For this reason a WSN scenario with $N=100$ nodes is selected and average lifetime per unit cost is measured for this WSN configuration. The results belong to this configuration are presented by Fig. 19. This results concern the alive nodes. Fig. 19 shows the lifetime per unit cost as a function of executed lifetime. It can be observed, in a middle size of WSN $(N=100)$ the average of lifetime per unit cost increases in a period of time from 500 to 5000 s.

This increment follows a positive slop above 4000 s. In the range of 4000 to 5000 s the system experiences the higher average lifetime per unit cost because of higher number of sensor death rate in this period of time in the network.

In summary, the clustering architecture of LEACH allows diminishing the communication by data aggregation which can minimize the number of Data/message to be transmitted. The experiment results demonstrated that the lifetime performance of LEACH is much superior to the flat kinds of WSN routing protocols for small scale network as compared to variants of the Directed Diffusion. Two-DD version has an extra reinforcement process and the large overhead that raises energy exhausted regions in the network results in increasing the transmission routes and diminishes network lifetime. In contrast to Two-DD, One-DD has much better lifetime performance but also less than the LEACH.

LEACH fails in the situations in which the higher energetic active nodes are concentrated, and if some nodes remain outside of any CH's group area they can die within a short period. Consequently, shifting the CHs and the residual energy metric are not enough to balance the energy consumption across the sensor network, and the CHs require to be distributed uniformly throughout entire network. Despite of this issue, in the small size of network (i.e. less than 100 nodes) it can increase significantly network lifetime. Also, because of the probabilistic approach of CH election in LEACH, total number of CHs for every round varies from that of optimized CH number. However, deploying either an extremely large or an extremely small number of sensors is inefficient in terms of network lifetime. By the same way, dividing the field in either very large or an extremely small number of clusters doesn't have any optimistic effect on prolonging the WSN lifetime. But in the large scale WSNs, LEACH (higher than 100 nodes) shows an extremely negative response in terms of the lifetime per unit cost.

IV. Discussion

The WSN lifetime issue has been analyzed by many researchers. Dietrich and Dressler have investigated a very concise overview on the WSN life time. They listed a summary of all factors that influences on network lifetime. Also, they introduced different metrics based on the context of WSN applications, including connected coverage, time integration, and service disruption tolerance [2].

Fengchao in [9] as well as Chen *et al.* in [25] studied lifetime-oriented single sink placement strategies to find the optimal strategy. Chen and his colleagues analyzed the lifetime per unit cost of a linear WSN, and they found out that deploying either an extremely large or an extremely minor amount of nodes is not efficient in terms of lifetime per unit cost. In [30] Halawani and Khan discussed different state-of-the-art protocols both in MAC and routing domains that were proposed for WSNs to compromise the overall goal of prolonging the network lifetime. Saraswat *et al.* in their survey on the techniques to improve WSN lifetime discussed different energy efficient routing techniques as well as the techniques that enhance the operational battery lifetime. They also explained about the photovoltaic cell for efficient power management in wireless sensor networks which are developed to increase the lifetime of the nodes [31]. Luo *et al.* proposed a routing protocol for sensor network with mobile sink [32]. They demonstrated the advantage of using a mobile sink rather than a static one. They simulated the networks with sensor nodes located in point lattices and in-building with nodes forming a ring. Based on their simulation results a mobile sink, in most cases increases the network lifetime with only a modestly degraded reliability in packet delivery. Malik and Qureshi in [33] analyzed the factors that can affect the WSN lifetime for cluster-based environments. They found out some significant elements that cause unbalanced energy utilization between nodes. Their experiment results highlighted the necessity for an adaptive and distributed clustering technique to prolong the network lifetime by additional balancing the energy consumption among the nodes. In [34] three WSN hierarchical protocols (LEACH, PEGASIS and VGA) are compared to find out the performance pertaining to network lifetime by Ahmed *et al.* They determined as WSNs do not have static topologies but the support for dynamic hierarchy lets hierarchical protocols to work in a longer period of time.

A static routing algorithm is proposed in [35] in order to extend network lifetime. Xenakis and his colleagues proposed an algorithm based on static routing among sensor nodes with unequal energy distribution based on the concept that sensor nodes do not need to exchange messages to inform one another about their residual energy levels. By using an iterative method they showed that their algorithm achieves longer lifetimes because each node is free from updating route information and less communication is required in the network. Finally in [36], Suarez and Renmarker implemented a Zigbee structure and showed that by incorporating the popular X-MAC power-saving MAC protocol into the ZigBee stack. They could significantly extend the lifetime of ZigBee net.

As said in all mentioned cases, there is a big concern for increasing the global network lifetime. Many of them are concentrated on improving the routing protocol to prolong network lifetime. This research explores single-sink WSN flat [9] and clustered scenarios by using two classic types of WSN routing protocol: Directed Diffusion that is a flat data-centric protocol and LEACH that is a cluster-based protocol. The experiments are designed and simulated using predefined sensor deployment strategies.

Actual work takes into consideration the lifetime as the main performance metric of a flat and clustered WSN.

The main key in this research is to study the performance evaluation of a WSN in terms of the global and per node lifetime. The performance evaluation in this study is evaluated under flat query cycle and cluster-based experimentations in the predefined deterministic and non-deterministic environments.

V. Conclusion and Future Work

This article explored the WSN lifetime and key factors that can have significant influences on the network lifetime. Among these key factors: first dead sensor, remaining energy, packet size and transmission range and their influences on the network lifetime were studied. The experiment scenarios were implemented in the flat and hierarchical WSN structures by using Directed Diffusion and LEACH protocols. The experiment results confirmed that the flat and cluster-based protocols can increases lifetime in different ways. One-DD and Two-DD are two Directed Diffusion variants flat protocols that used along with the LEACH which is the most popular cluster-based protocol.

Based on the fact that in large the networks, minimizing flooding and energy balancing between nodes is a significant benefit, the One-phase pull DD is more energy efficient than the Two-phase pull DD that can increase WSN lifetime much better than the Two-DD. This is due to the elimination reinforcement phase and exploratory message overhead in the WSN. The lifetime of WSN is extended by employing the uniform cluster settings and balancing the network loading among the clusters. In this role One-DD also beats the LEACH in the large scale WSN as well as Two-DD. Transmission range is another factor studied in this paper to control the lifetime of a flat and clustered WSN structures. According to the results obtained from experiments, the optimal lifetime for WSN will be obtained when the communication radius of the nodes is setup in the middle range of the communication. Increasing the sensor transmission range extremely larger or smaller than the middle operative range cannot help in extending the sensor network lifetime. This rule is observed in both LEACH and Directed diffusion protocols in different level of lifetime performance where LEACH can increase the stability WSN time of operation in a higher level than the One-DD and Two-DD respectively.

Finally, packet transmission and related issues are explored in order to study their effect on the network lifetime. Simulation results show that, the algorithms such as Directed Diffusion (both variants) that use multiple and alternative paths for the transmission of data from source to a single sink are significantly favored by deploying higher density of nodes around source and sink, since more paths can established around them. This ends to fewer ratios of packet drops while they prolong significantly WSN lifetime. The size of the packets has a key role in the lifetime performance in this type of routing algorithm. Simulation results confirmed that the small packets transferred across shortest routes significantly reduce the rate of consuming the energy as a results increasing the entire network lifetime. The process of energy balancing by employing small size of the data/message in the flat protocols is performed much better than the cluster-based types where CHs assume this role. Also, simulation results confirmed increasing size of the packets that are delivering over the routes or between routing nodes and their corresponding CHs means increasing more energy exhausting overhead in the system. Apart from this issue, it can be found an optimal range for packet size where the lifetime reduction issue is fixed. However, as the size of the transferred packets increases, load balancing process in both LEACH and Directed Diffusion will be more complicated and results to reducing significantly the stable operative time of the network.

This research studied a 2-dimension flat and hierarchical WSN structures and related issues to its lifetime. WSN lifetime is one of the active and strategic topics for researchers. My future strategic focus will be exploring the effective key factors that can prolong 3-D wireless sensor network architecture.

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