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Cluster-Based Node Placement Approach for Linear Pipeline Monitoring

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ABSTRACT Leakage in oil, gas, or water pipeline networks is a global concern; its impact has serious consequences on the ecosystem. Several solutions have been either proposed or in service for monitoring the pipeline networks. These proposals, however, are expensive, time-consuming, and most are intrusive which necessitate interrupting ongoing operations. The advances in sensing technologies made it possible to build affordable non-intrusive solutions. However, building a sensor network that is able to continuously monitor the pipeline, detect, and report any anomaly poses a number of challenges: node placement, energy saving, data flow, throughput, and just to mention a few. This paper presents an adaptive clustering algorithm for grouping and deploying multiple sensors along the whole pipeline. By using this algorithm, each group of sensors selects adaptively a cluster head, which aggregates the incoming traffic from its members and then delivers it to the next cluster head and so on until it reaches the base station. The simulation and prototype-based experiments' results have shown significant energy saving compared to contemporary approaches.

INDEX TERMS Wireless sensor networks, pipeline monitoring, linear topology, optimal node placement.

I. INTRODUCTION

The leak detection problem is a very challenging and critical issue. Solving this problem will save the nation lots of money, resources and more importantly, it will save the environment. The leak detection system can be broadly classified into continuous or non-continuous monitoring systems. In non-continuous monitoring systems, the inspection is performed at regular intervals. Depending on the mode of inspection, pipeline operations can either continue or need to stop. On the other hand, continuous monitoring systems monitor pipelines around the clock.

The advances in sensing technologies made it possible to build affordable non-intrusive continuous monitoring system. Wireless Sensor Networks (WSNs) have been proven to be a viable solution in many fields, including environmental monitoring, military surveillance, medical health care, emergency response and animal habits tracking [1], [2]. Typically, WSNs involve a large number of spread sensor nodes assigned to monitor/perform particular events and deployment of such sensors might be in uniformly or randomly. In a different way from the typical WSNs applications, WSNs can be applied for assessing the health status of key structures such as bridges, highways, pipelines, etc. [3]–[5].

On-line pipeline's monitoring is used to detect anomaly of these pipelines, but these types of WSNs require a careful attention because sensor nodes are placed linearly bringing many challenges related to routing, traffic management, lifetime, and power consumption. Among all these issues, the lifetime of the sensors nodes is the bottleneck due to their energy constraints [6]. Therefore, building a sensor network that is able to continuously monitor the pipeline, detect and report any anomaly is a big challenge.

The capabilities of WSNs to provide continuous monitoring of these pipelines is unsurpassed with the participation of the administrative humans. Detecting the problems in the early stages will enable the authorities to take preliminary precautions, guarantee public safety and protecting the environment. For example, detecting leakage in water pipelines could prevent major consequences, which may lead to financial loss and damage to people's health [7].

In general, most sensors are equipped with non-rechargeable or non-replaceable batteries having a limited energy which leads to shorten network lifetime especially,

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once they are deployed for long distance (e.g. pipelines monitoring applications) where these sensor nodes are expected to work for years. Therefore, power consumption is an important aspect affecting the performance and lifetime of WSNs strongly. Thus, it is crucial to design efficient and effective node placement approaches to achieve a maximum battery lifetime [8], [9]. In the literature, most of the works have concentrated on how to minimize the energy consumption per node thus maximizing the network lifetime. These approaches have limitations in defining an appropriate optimization problem which is difficult to be applied in real deployments. [10].

To address the aforementioned challenges, this work presents an adaptive clustering algorithm for grouping and deploying multiple sensors along a pipeline. We target WSNs used to detect leakage in water pipelines where the leak generates acoustical signals. By using this algorithm, each group of sensors selects adaptively a node to act as a cluster head which aggregates the incoming traffic from its members and then it delivers collected data to the next cluster head and so on until it reaches the base station. Clustering is predominantly beneficial techniques especially, for applications that require high scalability. In this context, the scalability means the need for load balancing, efficient resource usage, and reliable data aggregation. In addition, by taking the advantages of clustering techniques, this work also investigates the effects of the nodes placement on the lifetime targeting to maximize it and reduce energy consumption. The proposed approach is called equally-distance Equally Members approach (EDEM). EDEM gathers sensor nodes based on their power levels to balance the loads among each cluster and takes into account the required fidelity for the observed phenomenon. In EDEM, all clusters are assumed to have similar number of nodes.
The main contributions of this work can be summarized in the following points:

- Proposing an adaptive cluster-based node placement approach, EDEM, for on-line pipeline monitoring taking into consideration the observed phenomenon fidelity and node location.
- Studying the performance of the proposed approach via extensive simulation experiments and prototype experiments.
- Performing deep power consumption analysis for different ongoing processes such as CPU, transmitter, receiver, etc.

The rest of this paper is organized as follows: in section III the problem statement and system-level assumptions are discussed while the proposed approach is clarified in detail in section IV. The simulation experiments and results analyzing are discussed in section V while the real experiments are given in section VI to validate the simulation results. We conclude this work in section VII.

II. RELATED WORK

Sensor placement in WSNs has been widely studied by many researchers. For example, Lian *et al.* [11] have investigated unequally energy problem and suggested a strategy to non-uniformly distribute the sensors. Dense sensors increase as the distance gets closer to the base station. The simulation results showed that for dense networks, the total data capacity can be prolonged by an order of magnitude. In [12], unevenly consumed energy is identified in many-to-one sensor networks and to address this problem, the authors have proposed mobile sink and hierarchical structure for effective collection of data. However, most of these works are inapplicable to linear WSN due to the inherited characteristics of this topology. The authors in [13] proposed an algorithm to determine the optimal placement of data collector and find the optimal paths to carry out the data from underwater sensors to the onshore data collector. Also, this problem has been modeled as an integer linear program. In [14], [15], the authors have proposed an approach to place a minimum number of sensor nodes to perform relaying or sensing tasks for a specific duration. They have proved that this problem is NP-hard and derive a lower bound on the minimum number of sensors required.

Node placement problem for a linear topology has recently received a good attention. In [16], Tran et. al. have proposed a joint network coding and adaptive power control scheme in order to reduce the total power consumption and increase the bandwidth usage by regulating the transmission power. They claimed that their approach has shown effective results compared to the existing techniques. Guo *et al.* [17] have studied the node placement problem for oil pipelines monitoring under equal-power and equal-distance node placement schemes. They have proposed two heuristics to properly distribute the sensor nodes based on their power levels aiming to prolong network lifetime by appropriately increasing the density of the sensor nodes closer to the base-station and configure these nodes to carry/transmit the data at lower power levels. They have also suggested a mathematical model to validate their heuristics; their results showed that the network lifetime could increase up to 29% compared to equal distance placement approach. However, they have only used 6 of 31 power levels and their focusing was only in the transmission power. Moreover, this approach is not applicable for real deployment where exchanged messages need to be acknowledged by the receiver; this issue will be illustrated later.

The authors in [2] have investigated the node placement problem in linear WSN used for structural health monitoring with an objective to maximize the network lifetime. A methodology to find the optimal placement for the sensor nodes in this topology has been introduced. They have concluded that their methodology saves energy and extends the sensors lifetime.

Recently, Li *et al.* [18] have proposed a new algorithm based on compressive sensing to find the optimal number of nodes that can detect leakage in pipelines to avoid using huge number of sensor nodes and reduce the number of drill holes in these pipelines. However, it is impractical to apply such algorithm in real scenario due to network restrictions in

WSNs as the sensing range is limited and the sensor nodes are not able to capture the leak signal for a long distance.

As pointed out before, majority of researchers have studied the node placement problems in WSNs. Some works have been devoted to study WSNs used for pipeline monitoring where the sensor nodes are deployed linearly. However, few of these studies have adopted a realistic power model; no available work has considered all-discrete power levels in the available hardware. In addition, most of these works come up with greedy heuristic approaches which increase the density of sensor nodes with lower power level nearest to the base station. Also, all sensor nodes are responsible for carrying out the packets towards the BS all the time. Furthermore, these solutions may fail, in real environment, because the communication among neighbouring nodes can only work in one way (i.e. sender to receiver) which means that the reception sensor node cannot acknowledge the sender because its range is shorter than the range of the sender. Moreover, most of these previous works did not consider the required fidelity for detecting pipeline anomaly.

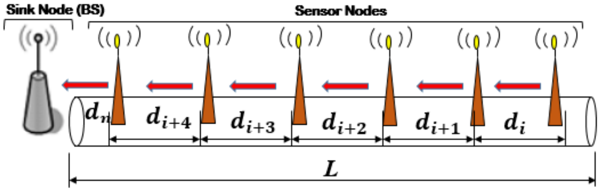


FIGURE 1. System architecture of the proposed pipeline monitoring sensor network.

III. PROBLEM STATEMENT AND SYSTEM-LEVEL ASSUMPTIONS

We consider a WSN comprised of multiple sensor nodes (SNs) placed on the outer surface of a pipe and ended with a BS as shown in figure 1. The SNs are deployed along the pipeline in gradually preselected sites. These SNs are in charge of data acquisition then they report periodically to the BS. All SNs play an important role in forwarding this data between the reported SN and the BS using multi-hop forwarding scheme. The data to be forwarded to the base station should be carried by the nodes located between the sender SN and the BS leading to extremely waste the energy of the sensor nodes closer to the BS due to highly asymmetric loads on these nodes. Finally, the BS after processing the received data judges whether a problem has already occurred or not.

The following enumerates the key system model assumptions:

1) Each sensor node is responsible for performing a periodic inspection within its sensing range.
2) All sensor nodes are homogeneous, i.e., have the same power model, communication capabilities, energy supply, etc.
3) Each SN delivers its packet to its neighbor towards the BS.
4) The distances between the adjacent *SNs* are equal due to the need for a reliable communication where the data is critical and the reported readings should be acknowledged. This procedure can not be performed using the greedy heuristics, proposed in [17], [19] where the receiver can not acknowledge the sender because its transmission range is shorter than the sender range as shown in figure 2.
5) The BS receives the data from all sensor nodes then, performs the required decision.

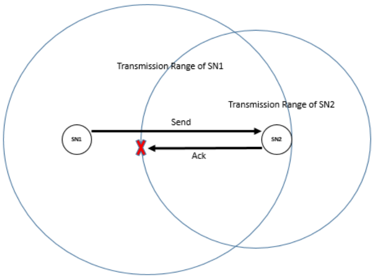


FIGURE 2. Illustration of the limitation of greedy heuristics due to inability of the receiver to acknowledge the sender.

A. SYSTEM MODEL

Lets L denotes the length of a pipeline ended by the monitoring unit (i.e. Base Station) that aggregates and summarizes the data, n denotes the sensor nodes along the pipeline, i denotes the specific sensor node where $1 \leq i \leq n$. Also, lets m to be the number of power levels (i.e. m=31 for TelosB, MicaZ) and each sensor node has a transmission power P_j with a communication range R_j where $j = 1, 2, 3, \ldots, m$. For instance, to transmit the data at power level j, the required power is P_j. A SN_i can be set to a different power level thus, it can communicate within different transmission ranges having different distance d_i as shown in Fig. 1. Figure 1 illustrates the architecture of the system under study.

We aim to determine the optimal number of sensor nodes needed to form clusters across the network subjecting to that the lifetime is maximized and total power consumption is minimized. Each sensor node has to be assigned to only one cluster c_r, where $1 \leq r \leq NCH$;, NCH is the number of clusters ($NCH \leq n$). Also, each sensor node can directly communicate with its cluster head (via a single or multiple hops).

IV. EQUALLY-DISTANCE EQUALLY MEMBERS APPROACH

In order to tackle the shortcomings of the greedy heuristic approaches, the length of the pipeline is divided into equal small segments and each segment should not exceed the maximum transmission range (e.g. 95m if TelosB mote is used). Each segment represents a cluster and has three sensor nodes where the distance between the adjacent sensor node must be less than or equal to 32m to achieve the required fidelity because the signal is acoustic [20] and it is essential to perfectly place more than the sensor node to detect the leak signals. The fidelity is assured by hearing the monitored phenomenon anomaly by multiple sensor nodes because if the failure in detecting the problem occurs in one side, another sensor(s) can detect and report to the BS.

$$d_{fid} \leq \frac{R_{max}}{n_{min}} \tag{1}$$

where d_{fid} is the optimal distance to assure the required sensing fidelity, R_{max} is the maximum transmission range and, n_{min} the minimum number of sensor nodes required to assure this fidelity.

Furthermore, all clusters have the same number of sensor nodes and the cluster head is responsible for forwarding the collected data from its group to the next cluster head towards the BS. In each cluster, the sensor nodes other than the cluster head transmit and forward the packets only within the same cluster to conserve the energy consumption.

Algorithm 1 Equally-Distance Equally Members (EDEM)

```
1 Input: n, L, and ($P_j$, $R_j$) with j = 1, . . ., m; //m=31
2 if ($n. R_m < L$) then
3     Exit: input parameters are not enough to cover the
        pipeline length;
4 end if
5 calculate number of clusters $NC = \frac{L}{R_m}$ //the number of
    clusters
6 If ($NC==n$)
7     Exit: all nodes transmit at maximum power and
        clustering impossible.
8 End if
9 $NMs = round(\frac{R_m}{R_8})$ //// number of members
10 If ($n < NMs * NC$) to obtain the required accuracy
11     Exit: The number of members do not achieve the
        required fidelity
12 End if
13 Start communicating based on dynamic EDEM
    Algorithm
```

A. ALGORITHM DESCRIPTION

Algorithms I & II illustrate the steps for running EDEM approach. First, Algorithm I checks (steps 2-4) if the number of sensors n is not adequate to cover the pipeline length L, the algorithm fails and exits. Otherwise, the sensors nodes are grouped into clusters based on maximum transmission range R_m (step 5) such that, the length of each cluster equals to R_m (i.e. $R_m = 95$ in CC2420 power model). In addition, each cluster selects one sensor node to be a leader to be in charge of forwarding the internal and incoming packets. The CH transmits at maximum transmission power. To start clustering, the number of SNs should be completely enough to form the clusters including at least three members (line 6-8). To guarantee the required fidelity, the distance between adjacent neighbors shouldn't exceed the corresponding fidelity distance (steps 9-12). The fidelity here means that the acoustic signal should be captured before it diminishes. Line 13 is the beginning of clustering mechanism and it is explained in the second algorithm. It starts by selecting the last SN in each cluster as a CH (step 1). Other SNs are set to transmit at power level 8. The steps 3 to 16 implement dynamic clustering process based on energy budget availability (steps 11 and 12) which are periodically checked to change the CHs (step 13 and 14).

Algorithm 2 EDEM Cluster Head Selection

```
1 Start by assigning the last SN in each cluster as a CH and
    start announcing
2 set $i = 1$
3 compute $Energy_{index} = \alpha E_{budget}$
4 For all SNs $SN_i \leq n$
5     Compute $Threshold = E_{budget} - Energy_{index}$
6     if $SN_i$ is CH
7         Set the transmission power to $P^{max}$
8     else // Normal sensor node
9         Set the transmission power to $P^8$
10     end if
11     check the energy budget of All CHs
12     if ($E_{budget} \leq Threshold$)
13         send advertisement 'I am NOT a CH'
14     Change the CH and for all other clusters change the
        CHs accordingly
15     end if
16 end for
```

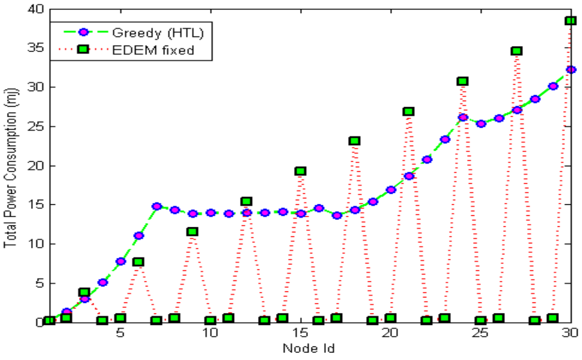
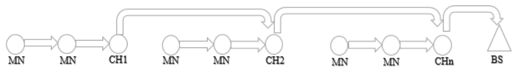


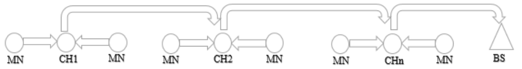
FIGURE 3. Comparison of power consumption of the clustering approach with a fixed cluster head and the greedy (HTL) approach; the number of sensors is 30.

B. DETAILED EXAMPLE

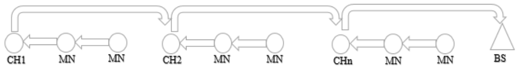
In order to illustrate the effect of the proposed clustering approach on power consumption, we simulate a small scenario when the pipeline length is 950 m and the number of sensor nodes is 30. However, this scenario is performed without dynamic clustering. The last sensor node in each cluster works as a CH all the time leading to drain out its energy quickly while the other sensor nodes still retain a huge amount of energy as depicted in Fig 3.



(a) The initial case where the cluster head is the last node in each cluster



(b) The second case where the cluster head is the middle node in each cluster



(c) The third case where the cluster head is the first node in each cluster

FIGURE 4. **Illustration of EDEM cluster head selection.**

This motivates the proposal of an adaptive clustering approach, where in each cluster, the leader (CH) is elected periodically among the cluster members to balance the energy consumption and every sensor node will serve as a CH in a periodic pattern. Fig 4a illustrates the first step when the last node in each cluster is assigned to be CH. This sensor node sends the packet at maximum transmission power to next CH towards the base station. Similarly, Figure 4b explains this mechanism when the CH changes to be the middle sensor node. In addition, Figure 4c shows this procedure when the first sensor node in each cluster works as a CH. The next two algorithms describe the mechanism of this approach. We assume that all sensor nodes are timely synchronized. So, the CHs in all clusters are elected simultaneously.

C. ALGORITHM THEORETICAL ANALYSIS

This section presents the analysis of the proposed approach in terms of power consumption and exchanged packets.

1) POWER CONSUMPTION MODEL

The total power consumption of each cluster is computed by calculating the inner power consumed by cluster members and the power consumed by the CH itself. It can be modeled as

$$E_{total_i} = EC_i + ECH_i \tag{2}$$

where EC_i is the intra-power consumption and ECH_i is the inter cluster head power consumption. The intra-power consumption is the energy consumed by the sensor nodes within the cluster while the inter-power consumption is the energy consumed by the CH of each cluster. The intra-power consumption EC_i can be calculated as

$$EC_i = \sum_{j=1}^{k-1} j * P_T * t + (j-1) * P_R * t \tag{3}$$

EC_i is the energy consumption of sensor nodes in cluster i and k is the number of sensors in each cluster distributed in EDEM. Also, P_T is the required transmission power for one packet, P_R is the required receiving power for one packet while t is the required time for transmitting or receiving a single packet. In addition, the inter-power consumption of the Cluster Head CH_i can be calculated as

$$ECH_i = (i * k) * P_C * t + (i * k - 1) * P_R * t \tag{4}$$

where P_C is the cluster assigned transmission power for one packet. Hence, the lifetime of the i^{th} cluster can also be calculated as:

$$LT_{c_i} = \frac{k.E_{budget}}{E_{total_i}} \tag{5}$$

On the other hand, for individual node, the lifetime can be calculated using the following equation:

$$LT_j = \frac{Ebudget_j}{E_j} \tag{6}$$

where j is the node index in cluster i.

Finally, from Eq. (4), the total power consumption can be computed as:

$$TotalPower = \sum_{i=1}^{C} ECH_i \tag{7}$$

where C is the number of clusters along the pipeline.

2) EXCHANGED PACKETS

As stated before, the pipeline network topology is linear which is inherently energy-hungry topology because of multiple hops that a packet should go through. EDEM is designed to minimize the number of hopes.

Theorem 1: Using EDEM, the number of exchanged packets would asymptotically drop by k folds compared to the greedy approach, where k is the cluster size.

Proof: Let the deployed sensor network is composed of n nodes, C clusters where each cluster is composed of k members ($k << n$).

For the greedy heuristic, the number of hops (H_{heur}) a packet sent by $SN_i + 1$ would traverse is $n - i$, where i is the sensor node index.

on the other hand, in EDEM approach, these hops (H_{EDEM}) equal to $k + (C - j)$, where C is the number of clusters, j is the cluster index.

In order to evaluate the gain of EDEM protocol, we will compute the ratio of hopes H_{heur}/H_{EDEM}.

$$\frac{H_{heur}}{H_{EDEM}} = \frac{n - i + 1}{k + C - j} \tag{8}$$

Without loss of generality, let $i = 1$ and $j = 1$ (i.e. first node in the first cluster). Then, since $k + C >> j$ equation 8 can be written as

$$\frac{H_{heur}}{H_{EDEM}} = \frac{n}{k + \frac{n}{k}} \tag{9}$$

TABLE 1. Simulation parameters.

Parameter	Value
Simulation Tool	MATLAB
Pipeline length	vary
Number of sensors nodes	vary
Battery capacity	2600 mAh
Battery Voltage	3 V
Sending/receiving one packet duration	1 second
Receiving power R_x	0.0564 Watt
Transmission Power P_T(member node)	0.0297 Watt
Transmission Power P_C(Cluster Head)	0.0510 Watt
d_{fid}	32m
D_{max}	95m
α	0.001

Simplifying the above equation, we have

$$\frac{H_{heur}}{H_{EDEM}} = \frac{k}{\frac{k^2}{n}+1} \tag{10}$$

Since $k << n$, taking the limit of the above ratio when $n \rightarrow \infty$ produces:

$$\lim_{n\to\infty} \frac{H_{heur}}{H_{EDEM}} = \lim_{n\to\infty} \frac{k}{\frac{k^2}{n}+1} = k \tag{11}$$

□

V. PERFORMANCE EVALUATION

We have conducted extensive simulation experiments examining the effectiveness of EDEM approach. The experiments have been repeated until 95% degree of confidence is achieved. MATLAB has been used to simulate the proposed EDEM approach with different pipeline lengths. The performance metrics used in this study are as follow.

1) Total power consumption: this metric measures the total energy consumption of each sensor node using equations in [19] for greedy approach and equations 3 and 4 for EDEM. This metric also shows the effectiveness of the EDEM in term of energy is conservation.
2) Network lifetime: this metric measures the estimated lifetime of each node using equation 4 in [19] for the greedy scheme and using equation 6 for EDEM. In addition, this metric shows the ability of EDEM in extending the lifetime of the deployed sensor network.
3) Total packets: this metric counts the number of packets that are passing across the network. This metric pinpoints the aggregated traffic in the network.

We have compared EDEM with the greedy approach proposed in [17], which is enhanced in [19] by adopting all power levels instead of 8 power levels. In the greedy approach, the density of the deployed sensor nodes increases as we get closer to the BS. Also, the farthest sensor nodes send at the maximum transmission power level while the closest SNs to the base station send at the minimum transmission power level.

A. SIMULATION RESULTS AND DISCUSSION

The performance evaluation of EDEM is considered under different scenarios. First, the sensor nodes are deployed using the greedy approach distribution based on the output vector V as in greedy algorithms [19]. Second, the sensor nodes are deployed based on EDEM approach by assigning the maximum power level, 31, to all cluster heads with equal distances (i.e. 32m) between all adjacent nodes (see the reference table in [19]). For a fair comparison, for both approaches, we have used the same number of nodes, but with different distances between nodes depending on the transmission ranges of the assigned power levels. For EDEM approach, the CHs are reelected periodically based on α value which is an indicator on the usage of battery level over a certain round; the lifetime increases as the α decreases. The tested scenario is for a pipeline of 950 m length, where α is varied from 0.01 up to 0.25. We can observe from Fig. 5 that the lifetime is strongly affected by α value, so we adopt the minimum value of α in all experiments.

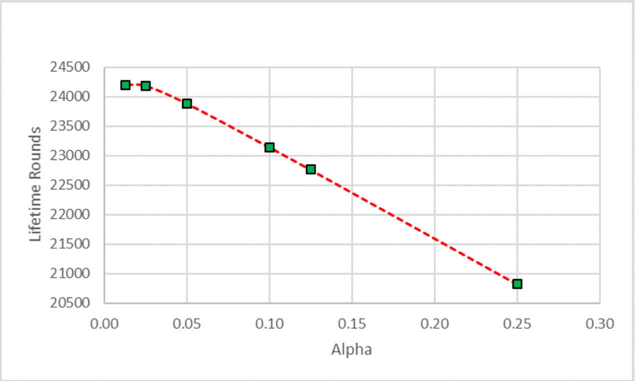


FIGURE 5. **The network lifetime; pipeline length is 950m, the number of sensors is 30 and different α.**

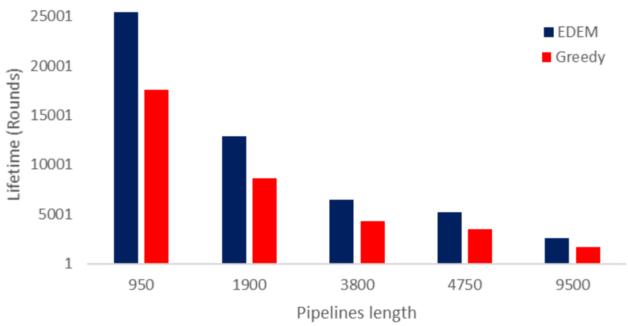


FIGURE 6. **The network lifetime for different pipeline lengths.**

Figure 6 shows the network lifetime using both approaches: the greedy approach and EDEM approach. It can be observed that in all scenarios, the performance of EDEM outperforms the greedy approach in terms of lifetime due to reducing the traffic load along the whole network and only particular nodes cooperatively carry out the packets towards the BS. The increasing ratio ranges from 56% up to 62% when the length of the pipeline is 950m and 9500m, respectively. However, for both approaches, increasing the length of pipeline significantly shortens the network lifetime due to huge traffic load passing across the network.

In addition, Fig. 7 illustrates the power consumption for all tested scenarios. We observe that EDEM approach is able to conserve energy across sensor nodes due to its ability to sharing loads among all cluster nodes to balance the consumed energy. In contrast, in the greedy approach, the last sensor node is working all time to forward the coming packets to BS. The amount of energy savings can reach 300% and up to more than 500%, when $L = 950$ and $L = 9500$, respectively due to reducing the required transmission and reception power.

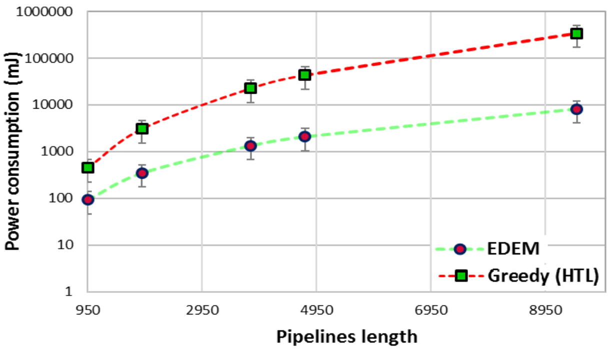


FIGURE 7. The power consumption for different pipeline lengths.

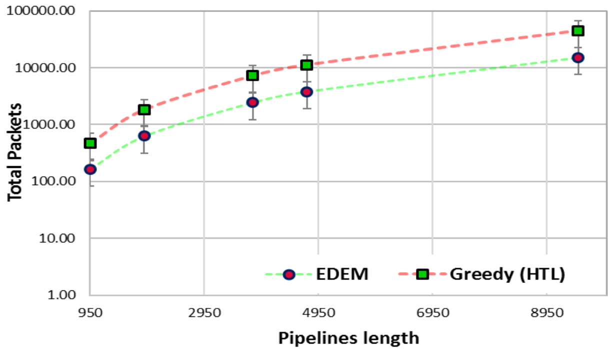


FIGURE 8. The total sent and forwarded packets for different pipeline lengths.

From the previous results, we can observe the outstanding performance of EDEM approach compared to greedy approach.

Moreover, the amount of sent and forwarded packets are dramatically decreased in case of EDEM approach as shown in Fig. 8 because the number of hops that the packets should pass though decreases significantly as proven in theorem 1.

VI. EXPERIMENTAL STUDY

In order to validate the simulation results, the aforementioned two approaches have been tested using real hardware devices in an outdoor environment.

A. METHODOLOGY

Due to unavailability of sufficient devices (i.e. 30 nodes) to be deployed over a pipeline of 950 m, we have only considered the last cluster; other clusters' traffic (i.e. nine clusters) is emulated as one node and fed to the cluster head of the last cluster.

We have carried out two different experiments (i.e. one for each approach) using real motes hardware. Each experiment has been repeated five times (.i.e. Each trial lasted 15 hours, we have collected over 75 hours of data for the running prototype) to obtain more reliable results and achieve 95% degree of confidence. We target to determine the effects of each deployment scheme on the sensor battery lifetime.

Our set of experimental studies have been implemented using TelosB motes. They have been supplied by new AA batteries each time to enable us providing valid comparison due to the effect of battery level on mote operations.

The experimental setup consists of the following parts:

- Emulation of 26 TelosB motes deployed along the 855 meters pipeline length; the last 95 m hosts the last cluster which has three TelosB motes.
- Mote#1 is connected to the gateway as a sink node to receive data from the other motes (Works as a base station).
- Gateway: Using serial dump tool to get data from the sink node's serial port and a terminal client running to capture these data.
- ContikiOS: used to program the motes in order to track the power consumption using *Energest* Module [21].

First, these motes have been deployed based on the output vector $\underline{V}$ of greedy algorithm, which identifies the transmission power level of each mote as illustrated in table 2. The distances between the motes are adopted based on the transmission range of each power level as in [19]).

TABLE 2. Power level assignment of greedy approach experiment.

Power level	31	24	20	15	11	8	5	4	3	2	1
Number of motes	6	1	1	1	1	1	1	2	7	5	4

Second, for the EDEM experiment, the same components are used but the deployment of motes is achieved based on our proposed algorithm which is explained in section IV. The distance between adjacent nodes is 32m. Each cluster covers a distance of 95m.

For logging the details of power consumption, we use Contiki's internal power profiling [21]. Contiki has a built-in power profiling module that measures the up-time of various components such as the radio duty cycle. For every sensor node in the network, the *Energest* module helps to track all power details. The *Energest* has been combined with the uploaded code to track the power and append the readings to the messages sent to the BS.

The following steps illustrate the procedure to estimate energy consumption:

1) Every SN collects its readings and reports to the BS every two minutes.
2) The time of sending and forwarding all packets in one round is called cycle.

3) For every mode of operation: transmission (Tx), reception (Rx), LPM, and CPU (illustrated in table 3), we compute the energy consumption of each mode based on its current consumption (e.g. The current of Tx at level 31 is 17.4 mA).
4) The total energy consumption of each cycle is calculated as explained in [22].
5) To calculate the overall energy consumption, P_{total} for all cycles is computed as follows.

$$P_{total} = P_{Tx} + P_{RX} + P_{LPM} + P_{CPU} \tag{12}$$

As illustrated in table 3, we have used TelosB mote with current in active mode is 1.8 mA, sleep mode 5.1 uA, TX varied from 8.5 to 17.4 based on adopted power level and the RX is 18.8 mA with fixed voltage at 3.V. Contiki OS enables us to track the time of how much every mode is in active state. All_Tx, for example, is the total (high) Tx time from the beginning of sensor operation, in the form of a number of ticks. So in order to estimate the energy consumption in a duration of time, we just consider the power incurred during that time by subtracting the current ALL_Tx reading from the previous ALL_Tx reading, because the Energest value is always incremented and never resets to zero.

TABLE 3. Prototype experiment parameters [23].

Parameter	Value
Contiki OS Ver	2.7
Number of sensor nodes	30
Pipeline length	950 meters
Tx current consumption	8.5-17.4 mA
Rx current consumption	18.8 mA
CPU current consumption	1.8 mA
LPM current consumption	5.1 uA
Voltage	3 V
Battery capacity	2600 mAh

B. CONTIKI OS

Contiki operating system is first developed by Adam Dunkels in 2002, and it is now maintained by the Swedish Institute of Computer Science (SICS) [21]. The Contiki community is one of the largest and most active IoT communities now. The Contiki OS is designed particularly for low-power wireless IoT devices with constrained memory and resources. Contiki manages a real-time clock and an event clock. System-level operation and low layer of network operation are scheduled and triggered by the real-time clock.

C. EXPERIMENTAL RESULTS AND DISCUSSION

The performance of aforementioned approaches has been investigated using different setups to explore the effect of using real sensors in outdoor environments. First, we demonstrate the effect of the greedy placement algorithm on the network lifetime and total energy consumption.

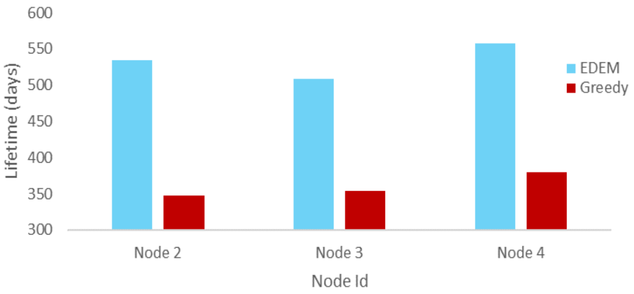
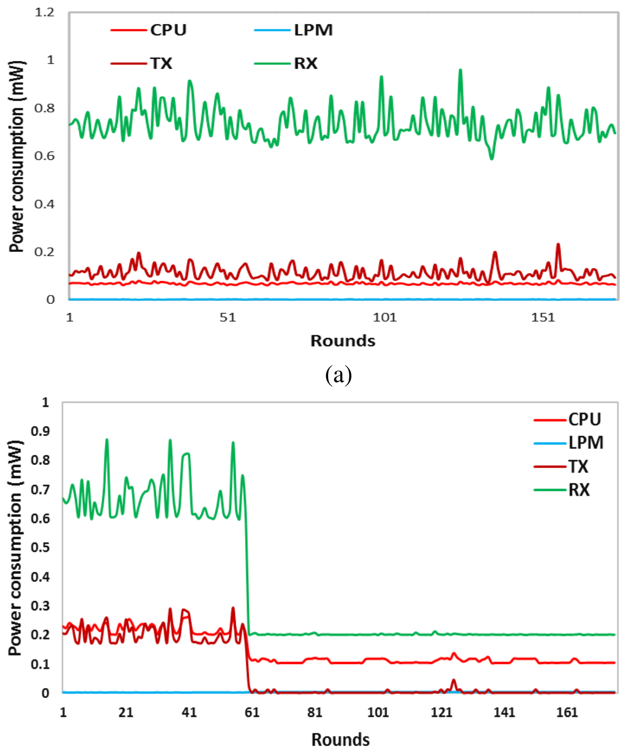


FIGURE 9. The lifetime of the greedy approach and EDEM approach; pipeline length is 950m and the number of sensors is 30.



(a)

(b)

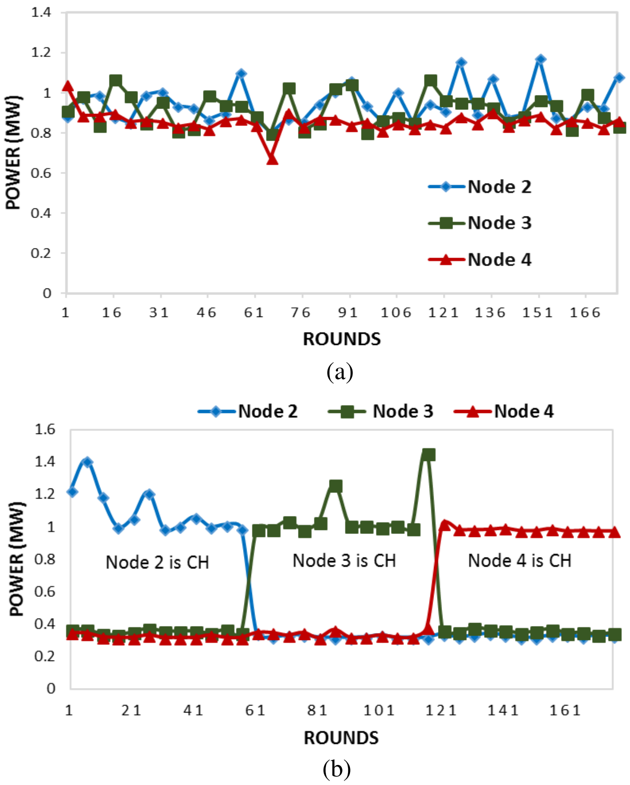
FIGURE 10. Illustration of instantaneous power consumption of each stage of the last sensor node; (a) greedy approach, (b) EDEM approach. 1-CPU stage. 2-LPM stage. 3-Transmission stage (TX). 4-Receiving stage (RX).

Figure 9 shows the lifetime of each node under both approaches. As we can notice, the lifetime, for the greedy approach, is dictated by the lifetime of node#2, nearest to the BS, because of its responsibility to forward all packets to the BS; leading to depleting its energy quickly. Also, this figure illustrates the lifetime of the other two nodes in the same cluster using the same power level. We can observe that the lifetime of the nodes decreases based on the distance to the BS. Furthermore, It can be concluded that EDEM can increase the lifetime by 50%. This enhancement in the lifetime can be attributed to the dynamic clustering and sharing loads among all clusters. The other normal sensor nodes just pass the packets within the same cluster towards their CH.

1) POWER CONSUMPTION ANALYSIS

We start with analyzing the details of the power consumption of each stage on sensor nodes to point out the enhancement of applying EDEM as shown in Fig. 10, including the four main stages: the transmitting stage (TX), the receiving stage (RX), LPM stage and CPU stage. The first peak of the TX and CPU stages indicates the wake up of the micro-controller unit, and the chip starts to do some preprocessing work, including message packaging and some hardware initiation.

Firstly, for the greedy approach, each stage still works at the same power level and consumes more energy all the time as depicted in Fig 10. On the other hand, for EDEM, since each node plays a different role, the power consumption is varied from stage to another overtime. If the sensor node acts as a CH, it consumes more power; otherwise, it consumes less power. Since nodes are alternating roles among each other, this behavior leads to conserve energy significantly.

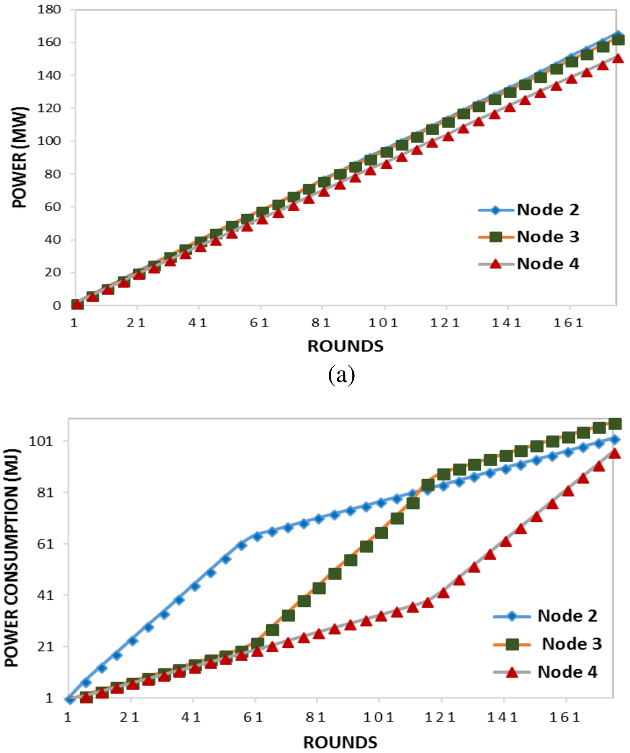


(a)

(b)

FIGURE 11. Illustration of instantaneous power consumption of the last cluster. (a) Greedy approach. (b) EDEM approach; pipeline length is 950 m and the number of sensors is 30.

Figure 11a depicts the instantaneous power consumption of each node in case of greedy approach deployment. We can observe that the nearest node to the BS (node 2) consumes the highest power all the time because it is forwarding all coming packets from the whole network. In contrast, for EDEM, we can notice that the power consumption of each node within the cluster is varied over the time depending on the node's role either CH with maximum power or normal node with minimum power as depicted in Fig.11b.



(a)

(b)

FIGURE 12. Accumulated power consumption of the last cluster. (a) Greedy approach. (b) EDEM approach. Pipeline length is 950 m and the number of sensors is 30.

In addition, Fig 12a presents the accumulated power consumption of all transactions for the greedy approach where the power consumption increases steadily in the same rate as the rounds increases. In this approach, each sensor node keeps consuming approximately the same power for all rounds during the operational time. Although, the cumulative power consumption at the end of the experiment is approximately similar for all nodes within the cluster, the last sensor node still consumes the highest power all the time.

On the other hand, for EDEM, the rate of power consumption changes depending on the role played in this round by the specific node as illustrated in 12b. Moreover, EDEM is able to save more than 38% of the total consumed power.

VII. CONCLUSION

Node placement for on-line pipelines monitoring application is a critical issue and has a deep influence on the whole network performance due to its effect on its scalability and lifetime. Exploiting the advantages of the clustering techniques, a novel clustering approach has been proposed aiming at maximizing the lifetime and reducing energy consumption of the whole network. Our approach (EDEM) prominently, gathers sensor nodes into clusters of equal members, considering their practical power levels available in motes' hardware. Each cluster head communicates directly with its neighbouring cluster head and so on until it reaches the base station node. The simulation experiments have been conducted under several scenarios and the results show 62% increment in the lifetime compared with the heuristics schemes.

Then, real prototype experiments have been conducted to validate the simulation results. Our set of experimental studies has been implemented using TelosB motes. The results show that the performance of the proposed approach outperforms the greedy approach and the lifetime can expand up to 50% more. In addition, in regard to power consumption, the results show that EDEM approach is very power-efficient and more suitable for linear topology networks than greedy approach. Although, EDEM was designed in this work for detecting leaks using acoustic signals, EDEM can easily be applied to other phenomena as far as the fidelity condition is satisfied.

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