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The Impact of Sensor Node Distribution on Routing Protocols Performance: A Comparitive Study

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Abstract—**The contemporary routing algorithms were built and tested under the assumption of uniformly distributed sensor nodes. However, this assumption is not always true. In some industrial applications and due to the scope of the ongoing monitoring process, sensors are installed and condensed in some area, while they are sparse in other areas. In this work, we investigate the impact of sensor node deployment distributions on the performance of different flavors of LEACH routing algorithm. Further, we study the impact of base station location, and different data loads. A comparison between LEACH and LEACH-C is conducted. The results show that different sensor distributions leads to significant differences in network performance. Furthermore, it shows that LEACH-C out performs LEACH almost in all distributions variations and base station locations.**

Keywords-Sensor networks; Deployment distributions; Routing protocol; LEACH; WSN;

I. INTRODUCTION

A wireless sensor network (WSN) consists of spatially distributed autonomous and battery-powered sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and to cooperatively pass their data through the network to a main location (i.e., base station or sink). In recent years wireless sensor networks have a wide range of application; such as battlefield surveillance in military applications, industrial process automation (monitoring and controlling), meteorological areas, home appliances, and health applications [6]. However, wireless sensor nodes have limited resources in terms of processing, storage, and communication capabilities and using existing routing protocols for ad-hoc networks is not efficient. Therefore, power-aware routing protocols have been proposed and several surveys and comparison studies have been conducted [17] [9] [11].

All these studies have explored the performance of routing protocols under the assumption of uniformly distributed or deployed sensor nodes in the area of interest. However, this assumption is not always true especially in industrial networks where the ongoing applications determine the location of a sensor node to monitor and control a specific region or a machine, whereas in military applications it might be deployed by throwing them from a plane that may resemble a normal distributed scenario. Therefore, it is important to study the impact of random distributions other than uniform distribution on the specific routing protocols.

The contributions of this work are two folds. First, we study the impact of exponentially distributed sensor nodes as well as normally distributed sensor nodes on the performance of the well known routing protocols, namely, LEACH and its extension LEACH-C [12] [13] [14]. To the best of our knowledge, this issue has not been investigated well in the literature.

Second, this work also, investigates the behavior of these routing protocols under real scenarios of data availability for transmission in each sensor node. Most of the existing studies assume that the sensor always has data to send which makes the network fully loaded during the whole network life time. However, in real WSN the sensors vary from one to other in data rate transmission based on their region conditions, e.g. motion detection monitoring. This paper has studied the effect of different data rates on WSN routing protocols and how that affects the network performance.

The rest of this paper is organized as follows. Section II discussed the related work and briefly describes Leach and Leach-c routing protocols. Section III discusses the different scenarios that are used in our study including the different combinations of different distributions with different base station locations. Simulation setup and result analysis are presented in section IV. We conclude our paper in section I with a summary of findings and a brief discussion of future work with open research issues.

II. RELATED WORK

Some non-uniform deployment strategies have been studied in past published works. However none of them has studied the impact of these distributions on WSN routing protocols. Lian et al. [2] focused on increasing the total data capacity by only considering the energy spent on the data transmission. They found that in a uniformly distributed homogenous WSN with a static base station, after the lifetime of the network is over, up to 90 percent of the total initial energy remains unused. They proposed a non-uniform sensor distribution strategy by adding more nodes to the heavier energy load area, and thereby maximizing the network life time by balancing the energy consumption over nodes. Their simulation showed that the strategy can increase the total data capacity by an order of magnitude.

Wu et al. [3] also addressed the energy hole problem in WSNs with non-uniform node distribution. They investigate the theoretical aspects of the non-uniform node distribution strategy, which aims to avoid the energy hole around the sink .They assumed that each sensor generates data for each data collection period, which may not be true for highly dense WSNs. They provided a non-uniform node distribution strategy, which makes the number of nodes increase with geometric proportion from the outer parts to the inner parts of the network, which looks like normal distribution. Simulation experiments demonstrate that when the network lifetime has ended, the nodes in the inner parts of the network achieve nearly balanced energy depletion, and only less than 10% of the total energy is wasted. In [4], Liu et al. proposed a non-uniform deployment scheme based on a general sensor application model. They derived a function to determine the number of nodes as a function of the distance from the sink. They also assumed that each sensor is required to report the data back to the sink. Simulations show that their method can enhance the network lifetime.

All these non-uniform deployment strategies are focused on accurately controlling the location of sensors in the network domain for achieving a higher lifetime. In some real applications, it is hard to strictly control the number of nodes in a given domain, e.g., the sensors are dropped from a helicopter or a low-flying unmanned aerial vehicle. Zou and Chakrabarty [1] suggested the placement of airdropped sensors as 2D Gaussian distribution without giving any specific results. Demin et al. [5] argue that an appropriate strategy can be employed when dropping sensors from a plane to have the standard deviation of the 2D Gaussian distribution. For instance, this can be performed by controlling the height of the plane or using some specific devices to eject sensors with different circular angles. Therefore, distribution of sensors could satisfy 2D Gaussian distribution and follows a predefined standard deviation with the center point at the drop point of the helicopter. This enables sensors to have a higher probability to be deployed near the drop point than the uniform deployment. The benefit of it is that this relaxes the energy hole problem and increases the WSN lifetime.

Demin et al. [5] investigate the Gaussian distribution as a deployment strategy in WSNs. Their study was focused on two important design factors for such a WSN deployment strategy, the lifetime and coverage. In this work, they have provided theoretical formulations for lifetime and coverage in a WSN based on 2D Gaussian distribution. Two types of dispersions are considered: $\sigma x=\sigma y$ and $\sigma x\neq\sigma y$ .The analytical model captures the intrinsic properties of the coverage and the lifetime by using various parameters. They show that the Gaussian distribution can effectively increase the lifetime. The analytical results could serve as the WSN design guideline. For this purpose, they have developed two algorithms to compute the optimal deployment strategy and show that the optimal deployment strategy can be obtained in a polynomial time complexity. Although they came out of the general nature of previous studies by including a non-uniform distribution in their study, their study didn't show the impact of Gaussian distribution deployment on the existence WSN routing protocols, e.g. leach.

Wu and Chen in [7] propose a partition-based hybrid clustering routing protocol (named PHCR). To address the problem that the cluster-heads is distributed unevenly in the network, they divided the network monitored area into several sectors through the partition algorithm. In the first round, the sensor node which is the nearest to the area center is selected as the cluster heads by the sink node, and the other nodes in each sector become the member nodes. The sensor node which is the second closest to the sector center is selected as the cluster head for the 2nd round. After the 2nd round, the cluster head of the next round is chosen by the prior cluster head of its own cluster. Simulation results show that PHCR improve the network lifetime effectively.

Sara et al. [15] studied the effect of node distributions on lifetime of WSNs. Unlike our study, they focus on prolonging the network lifetime by investigating different node deployments including both geometric and uniform. Geometric distributions are represented by star topologies with different variations of number of star brunches and number of nodes in each brunch. They found that the 3x33 star resulted in the highest network lifetime for a 100x100m. It produced 4612 cycles, exceeding random distributions results by 1212 cycles. This result was taken a step further by applying other base station locations.

Peng et al. [16] they studied the impact of sensor node distributions on coverage in sensor networks as the coverage is an important QoS measurement for many sensor network applications. They first show the impacts on network coverage by adopting different sensor node distributions through both analytical and simulation studies. They observe that assumed different sensor distributions may lead to significant differences in coverage estimation. They adopt a distribution-free approach to study network coverage, in which no assumption of probability distribution of sensor node locations are needed. Although they only study the network coverage, they believe that their methodology can be generalized and extended to estimate of other sensor network performance metrics.

In the following subsections, we briefly introduce the basics of LEACH and LEACH-C.

A. LEACH

One of the most popular hierarchical routing protocols for wireless sensor networks is Low Energy Adaptive Clustering Hierarchy (LEACH) [12] [13] [14]. LEACH is a clustering -based communication protocol proposed by the MIT LEACH project. The idea is to form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. This will save energy since the transmissions will only be done by such cluster heads rather than all sensor nodes.

In LEACH, nodes are organized into local clusters, with one node acting as the local base station (BS) or cluster – head as seen on figure 1. All the other nodes must transmit their data to the cluster heads, while the cluster-head nodes must receive data from all the cluster members, perform signal processing functions on the data (e.g., data aggregation), and then transmit data to the remote base station. Because a cluster head is doing much more work and stay on all the time, so being a cluster head is much more energy-intensive than being a non-cluster head node. In order to evenly distribute the energy load associated with a cluster head and avoid draining the battery of any one sensor, cluster head position is rotated randomly among all the nodes.

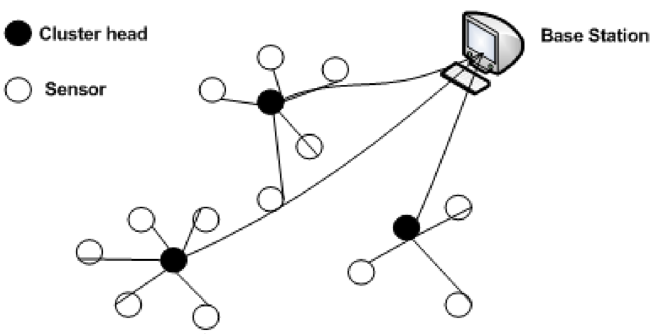

Figure 1: Cluster head formation in LEACH

The medium access protocol in LEACH is also chosen to reduce energy dissipation in non -cluster -head nodes. Since a cluster head node knows all the cluster members, it can act as a local control center and create a TDMA schedule that allocates time slots for each cluster member. This allows the nodes to remain in the sleep state as long as possible. In addition, using a TDMA schedule prevents intra-cluster collisions.

B. LEACH-C

While there are advantages for using LEACH, this protocol offers no guarantee about the placement and/or number of cluster head nodes. Since the clusters are adaptive, obtaining a poor clustering set-up during a given round will not greatly affect overall performance. However, using a central control algorithm to form the clusters may produce better clusters by dispersing the cluster head nodes throughout the network. This is the basis for LEACH-centralized (LEACH-C), a protocol that uses a centralized clustering algorithm and the same steady-state protocol as LEACH.

During the set-up phase of LEACH-C, each node sends information about its current location (possibly determined using a GPS receiver) and energy level to the BS. In addition to determining good clusters, the BS needs to ensure that the energy load is evenly distributed among all the nodes. To do this, the BS computes the average node energy, and whichever nodes have energy below this average cannot be cluster heads for the current round. Using the remaining nodes as possible cluster heads, the BS finds clusters using the simulated annealing algorithm to solve the NP-hard problem of finding optimal clusters. This algorithm attempts to minimize the amount of energy for the non-cluster head nodes to transmit their data to the cluster head, by minimizing the total sum of squared distances between all the non-cluster head nodes and the closest cluster head.

Once the cluster heads and associated clusters are found, the BS broadcasts a message that contains the cluster head ID for each node. If a node’s cluster head ID matches its own ID, the node is a cluster head; otherwise, the node determines its TDMA slot for data transmission and goes to sleep until it is time to transmit data. The steady-state phase of LEACH-C is identical to that of LEACH.

III. RANDOM NODE DEPLOYMENT DISTRIBUTION

The impact of sensors deployment and different data rates on the WSN performance, lifetime and energy consumption has not get enough attention in the literature. In this study, we have done intensive performance evaluation for three different deployment distributions: uniform, normal, and exponential and we use the performance under uniform distribution as our benchmark. Figure 2 shows a snapshot of one of the uniform topologies that we have used in our simulations.

For more accuracy, we used ten different topologies for each distribution in our simulation. Thereby, each single data point in our results is an average of ten different topologies. One snapshot for each distribution is illustrated here. As shown in Figure 3, in case of Normal distributed nodes, the majority of nodes are concentrated at the center of the field. The normal distribution parameters were 50 for the mean and 25 the standard deviation. On the hand, in case of exponentially distributed nodes as shown in Figure 4, the majority of the nodes are concentrated at the corner. The exponential distribution parameter lambda was 35 (the distributions’ parameters are experimentally determined after performing many simulations); thus the location of base station plays a key role in the overall network performance as will be explained later.

The figures also show the different positions of the base stations (sink nodes); for each distribution we have considered two scenarios, one with central base station (50, 50), and the other with corner base station (5, 5). In this way, we have simulated the all possible combinations of the distributions with base station locations.

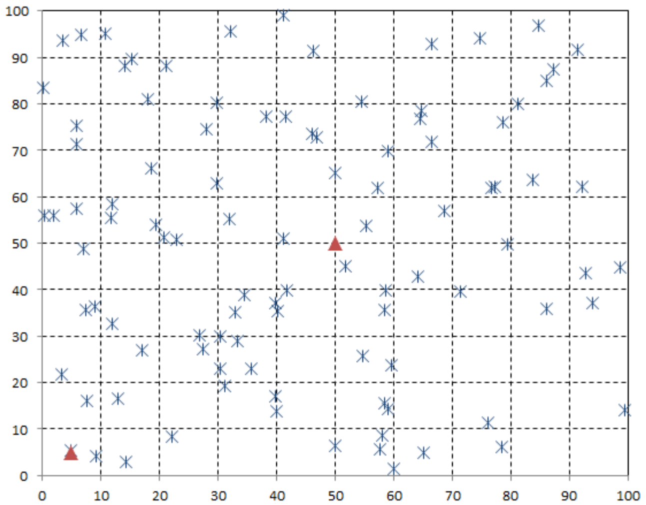

Figure 2: Uniform distribution with different base station locations (Red tringles)

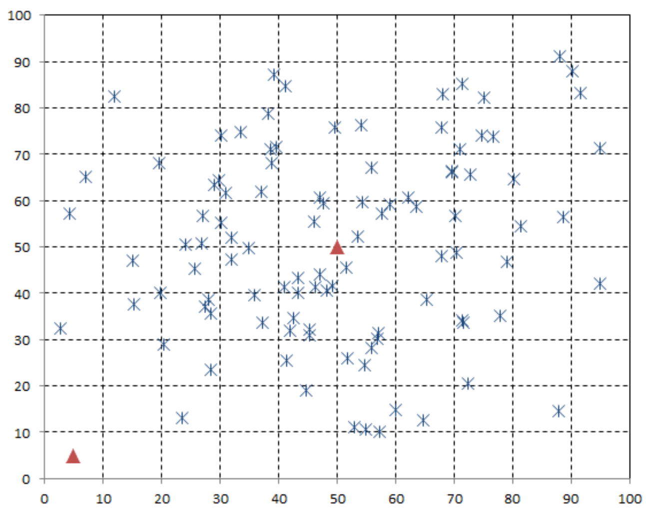

Figure 3: Normal distribution with diffrent BS locations locations (Red tringles)

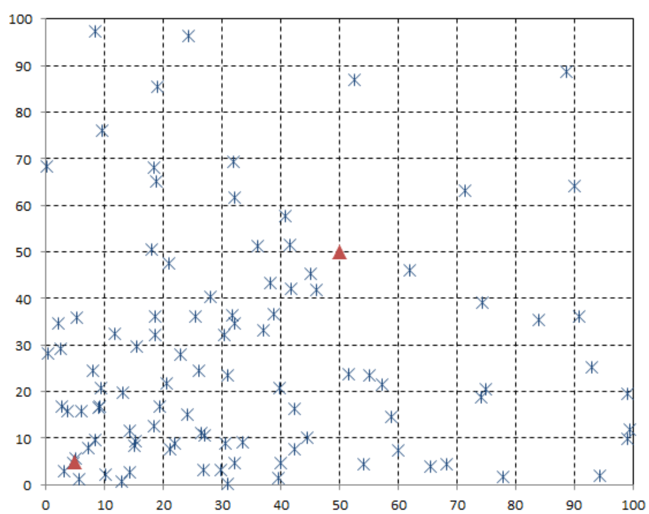

Figure 4: Exponential distribution with different BS locations locations (Red tringles)

IV. Simulation and Resutl Analysis

A. Simulation setup

Here we discuss the simulation environment in details for each scenario. We have used the popular NS-2 simulator [10] to investigate our problem. The leach extension (A Low-Energy Protocol Simulator for Wireless Networks) has been integrated with NS using the tools in [8]. We have encountered on bug in the code when we revised the total energy consumption and we observe that it was much bigger than the total initial energy. We have spent a lot of time investigating this problem and finally we come up with some modification on the code, specifically adding if statement before changing the node energy level. After that we verified our solution by simulating different examples. For the number of cluster heads in each scenario, we use 5% of the total number of nodes (this is based on published paper and also recommended by the NS-Leach code documentation). Considering the availability of data for transmission in each sensor node, we emulate this phenomenon by forcing the sensor node to sleep 0%, 25%, 50%, and 75% of the TDMA frame cycle, where 0% means that the entire time slots are occupied with signals, none of them is empty. The energy model and other simulation parameters are summarized in tables 1 and 2.

To evaluate the performance of LEACH and LEACH-C, we use the ratio of total delivered packets to the base station to the total energy consumption (packet/joule). This metric is more practical that the typical measure (i.e. total packets or total energy) as it combines two measures in one and gives how much energy should be invested to get a data packet at the base station. To ensure 90% confidence in the obtained results, for each point in our curves, we have developed multiple random topologies for each distribution and then we average the collected results.

Table 1: Simulation parameters

Parameter	Value
Simulation time	500 sec
Number of nodes	50,100,150,200,250
Simulation area	100 x 100 m2
Number of runs per scenario	10 times
Base stations' positions	Corner(5,5) & Center (50,50)
Number of cluster heads	5% of number of nodes
Round time	50 sec
Data signal size	525 bytes
Channel BW	1Mbps

Table 2: Energy model parameters

Parameter	Value
Initial energy	5 joule
Electronics energy	50 nJ/bit
Receive threshold	1 nJ
Success threshold	6 nJ
Data aggregation energy	5 nJ/bit/signal

B. Results and analysis

In this section, we present our findings. To ease the presentation of our results, we use the following notations:

- leachCnNd: Leach with BS located at the center and normally distributed nodes,
- leachCrNd: Leach with BS located at the corner and normally distributed nodes,
- leachCnUd: Leach with BS located at the center and uniformly distributed nodes,
- leachCrUd: Leach with BS located at the corner and uniformly distributed nodes
- leachCnEd: Leach with BS located at the center and exponentially distributed nodes,
- leachCrEd: Leach with BS located at the corner and exponentially distributed nodes

First, we start with discussing the impact of different random distributions on LEACH where the base station is located either at the center or at the corner.

C. Impact of Different distributions

As shown in Figure 5, normally distributed topologies show more efficient utilization of energy when number of nodes is 50 nodes compared to exponential or uniform distributions. However, for other configurations, In addition, as number of sensor nodes increase the network becomes less efficient in utilizing energy and this applies to all distributions and base station locations. Table 3 summarizes the improvement over uniform distribution assumption. The presented numbers are normalized values compared to the performance under uniform assumption

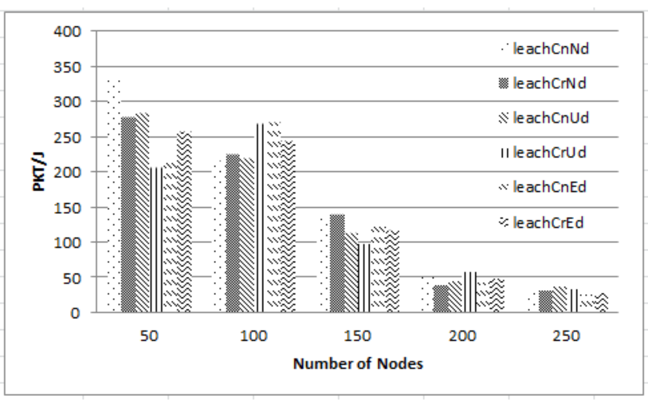

Figure 5: LEACH with different distributions and different BS locations

Table 3: LEACH – Improvement compared to uniform deployment

# of nodes	Exponential		Normal	
	Corner BS	Center BS	Corner BS	Center BS
50	1.245813	0.761704	1.353098	1.176483
100	0.909472	1.233777	0.839588	0.985673
150	1.17898	1.118575	1.415562	1.214714
200	0.852851	0.97859	0.693349	1.117548
250	0.821225	0.709228	0.967667	0.819231

On the other hand, considering LEACH-C routing protocol, we can observe its consistency in achieving better performance as shown in Figure 6 & 7. Moreover, LEACH-C always outperforms LEACH. For example, for 50-node topology, LEACH-C can deliver around 700 packets per joule; whereas in case of LEACH, the maximum around 300 packets per joule which is nearly half of LEACH-C. This result can be attributed to the centralized in cluster heads selection which yields better load balancing over network nodes. Also, in both protocols as we increase the number of nodes the performance degrades, that is due to the increase of data collisions. However, in some cases such as LEACH uniform distribution, the best case was in 100 nodes where the network approaches its peak performance.

Table 4 summarizes the improvement over uniform distribution assumption. It is interesting to notice that in case of exponentially distributed topologies, locating the base station at the corner of the network shows a clear improvement compared to uniform distribution. This result is very intuitive as most of the nodes are concentrated at the corner as shown in Figure 4. However, the surprising result is for the case of normally distributed topologies which also illustrate outstanding performance when the base station is located at the corner.

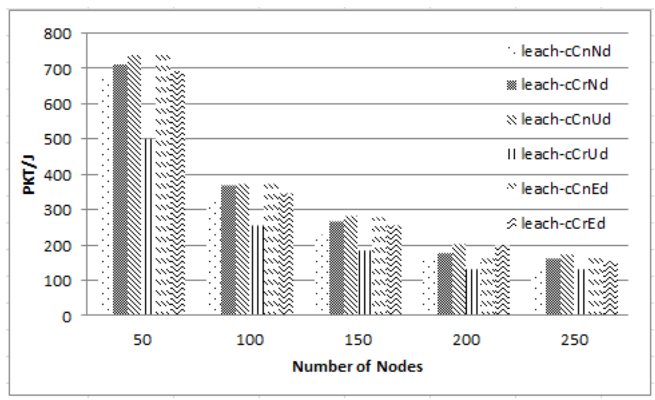

Figure 6: LEACH-C with different distributions and different BS locations

Table 4: LEACH-C- Improvement compared to uniform deployment

# of nodes	Exponential		Normal	
	Corner BS	Center BS	Corner BS	Center BS
50	1.3856	1.014493	1.419415	0.909443
100	1.343665	0.99449	1.436312	0.869909
150	1.374118	0.987334	1.434947	0.817295
200	1.546294	0.799939	1.354802	0.818621
250	1.191354	0.974076	1.229989	0.762908

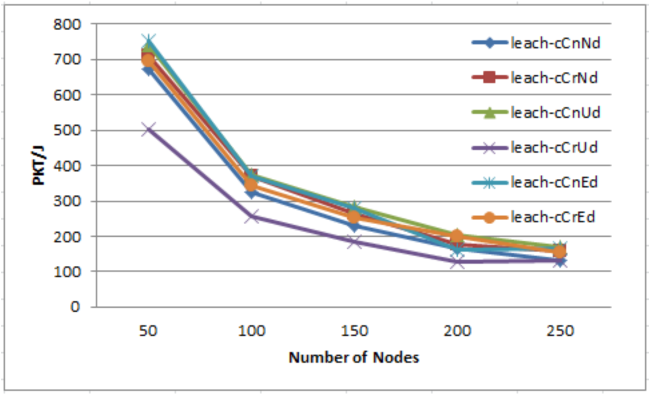

Figure 7: LEACH-C with distributions and different BS locations

The scenario of exponential distribution with center location base station has been chosen as a comparison scenario between leach and leach-c as shown in Figure 8. It is obvious that leach-c outperform leach in all network's state, especially in case of low number of nodes, 50 nodes.

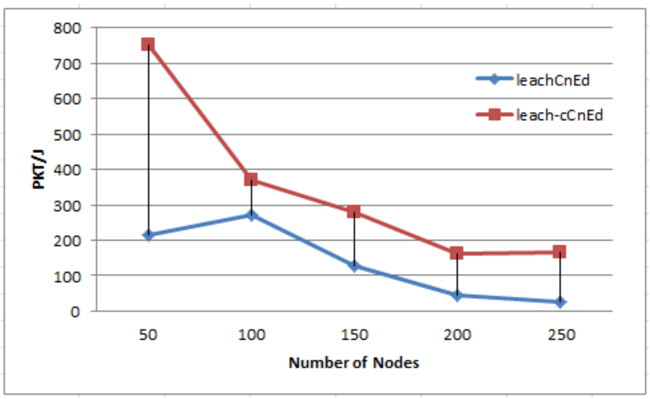

Figure 8: LEACH and LEACH-C comparison with exponential center BS

D. *Routing Performance under Variable Data Rate*

In the previous section, we assume that a sensor node always has data to transmit. Nonetheless, in real life application, this assumption might not be true where the data rate varies from node to node based on several reasons such as the monitored event, the monitored area, etc. for example, in surveillance applications some of them do not sending anything unless there is a detection for movements (movement detection surveillance).

In this section, we consider variable data rate for sensor nodes, and we study the performance of LEACH and LEACH-C for four different data rates. In our simulation experiments, different data rates means that the node within the cluster can send nothing in its TDMA slot time (i.e. slot is reserved but no data to transmit). Hence, we expect LEACH routing protocol not to perform well many slots will not be utilized while the cluster head is active waiting for data to be transmitted. Figures 9& 10 depict the performance of LEACH for exponentially distributed topologies under different data rates. We can clearly observe the high drop in derived data compared to 100% activity case. Of course as the node is only 25% active, we may expect the delivered data to drop by 25% also. However, the actual drop is about 90%. Again, as we note above that LEACH can behave unpredictably. For example, for the case of 75% activity and the base station is located in the center, the delivered packet per joule is higher than the 100% case. We hint to this behavior by negative sign in Table 5.

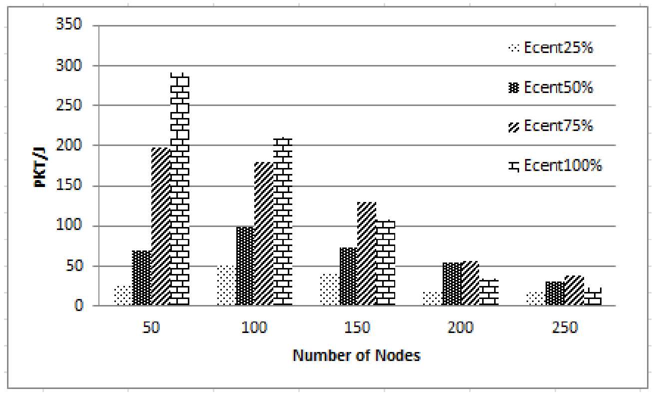

Figure 9: LEACH with different data rates and Exp. Center BS

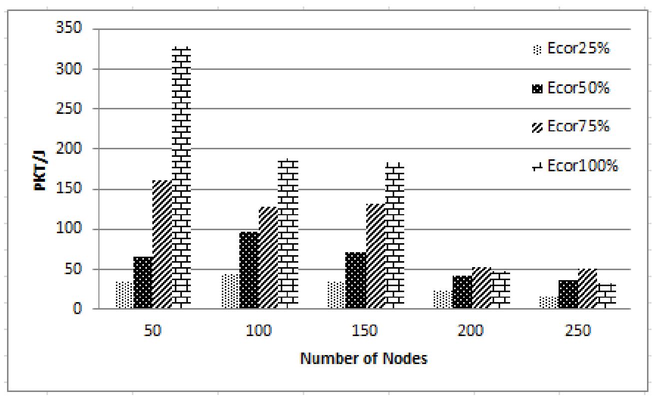

Figure 10: LEACH with different data rates and Exp. Corner BS

Table 5: Drop in efficiency compared to 100% under LEACH with different data rate and exponential sensor nodes deployment

# of nodes	Data Rate 25%		Data Rate 50%		Data Rate 75%	
	Corner BS	Center BS	Corner BS	Center BS	Corner BS	Center BS
50	90%	91%	80%	76%	51%	33%
100	77%	75%	48%	53%	32%	15%
150	82%	64%	61%	33%	28%	-20%
200	53%	46%	11%	-61%	-13%	-66%
250	52%	26%	-13%	-29%	-58%	-62%

Figures 11 & 12 show the energy consumption efficiency under LEAH-C for centered base station and cornered base station respectively. LEACH-C behaves in a similar manner compared to LEACH but LEACH-C is more consistent.

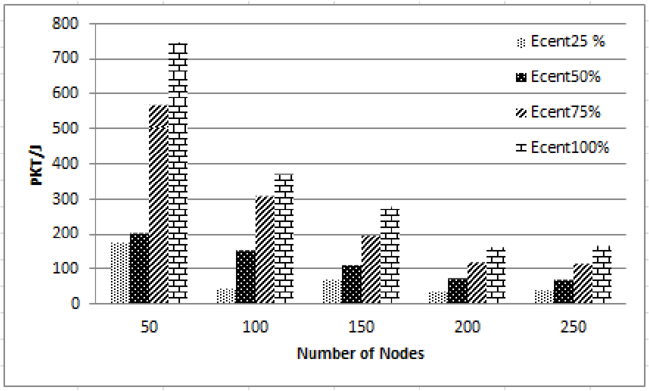

Figure 11: LEACH-C with different data rates and Exp. center

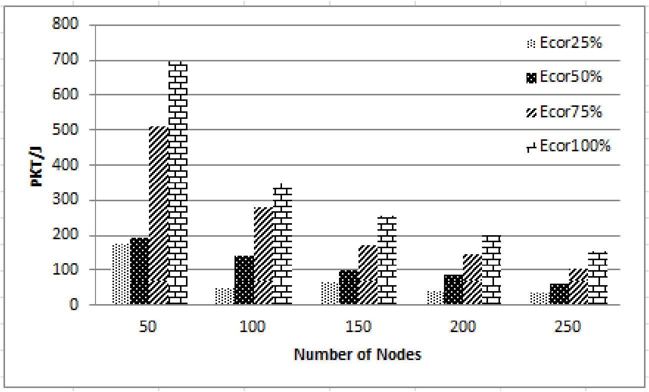

Figure 12: LEACH-C with different data rates and Exp. Corner BS

Table 6: Drop in efficiency compared to 100% under LEACH-C with different data rate and exponential sensor nodes deployment

# of nodes	Data Rate 25%		Data Rate 50%		Data Rate 75%	
	Corner BS	Center BS	Corner BS	Center BS	Corner BS	Center BS
50	75%	77%	73%	73%	26%	24%
100	87%	88%	59%	59%	19%	17%
150	75%	76%	61%	61%	33%	30%
200	80%	79%	58%	56%	28%	28%
250	77%	76%	60%	58%	33%	31%

I. CONCLUSION AND FUTURE WORK

The huge demand for efficient and practical deployment of wireless sensor networks pushes towards revisiting the existing protocols looking for better understanding and novel solution. This paper is one step in this direction where we studied the impact of different sensor nodes deployments and characterized the behavior of well-known routing protocols such as LEACH and LEACH-C. Moreover, in this work, we investigated the performance of LEACH and LEACH-C for different data rate availability.

As future directions, we intend to study in depth Cluster head characterization and formation. Also, it is important to revisit the validation of the assumption that 5% nodes to be cluster heads. Finally, we are working on devising an Adaptive TDMA protocol to accompany LEACH or its flavors.

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