Quantitative Scalability of Nodes and Geographical Coverage in LEACH Protocol

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***Abstract*—Energy optimisation using clustering remains a constant challenge in wireless sensor networks (WSNs). The high volume of data generated within these networks leads to excessive energy consumption when transferring it to the processing center. Therefore, clustering protocols, in particularly hierarchical routing protocols dedicated to WSNs, must imperatively integrate energy efficiency mechanisms in order to extend the functional lifetime of the nodes and the network. In this paper, we focus on an in-depth analysis of scalability in the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. The LEACH protocol, renowned for its random and distributed approach to WSNs energy optimisation, forms the focus of our analysis and exploration. Our study focuses in particular on the quantitative scalability of nodes and the scalability of geographical coverage. The aim is to improve our understanding of the behaviour of the LEACH protocol in large-scale environments, particularly with regard to node and network lifetime and energy management parameters.**

***Index Terms*—LEACH, Energy optimisation, WSNs, Clustering, Quantitative scalability, Geographical scalability, Lifetime parameters.**

I. Introduction

THE advances in the Internet of Things (IoT) and WSNs have brought about significant transformations in various domains including cities, homes, industry, agriculture, transport and health, with billions of interconnected intelligent devices [1]. We must not ignore advances in electric vehicle technology, as [2] [3] points out. The IoT, based on technologies such as Radio-Frequency Identification (RFID), smart sensors and Internet protocols, is driven by concepts such as ubiquitous computing and WSNs [4]. At the heart of this revolution, WSNs are positioning themselves as essential elements, but their energy efficiency remains a major challenge. Energy optimisation mechanisms, classified into five categories [5], have been defined to overcome this challenge. Among these mechanisms, data aggregation, especially using clustering, has emerged as a crucial strategy for reducing energy consumption [6]. Our in-depth study of Scalability in the LEACH Protocol focuses on two fundamental aspects: the quantitative scalability of nodes and the observed geographical coverage. These two scalability dimensions are of critical importance in optimising the performance of a large-scale clustering protocol. Energy efficiency and moderate mortality rates, particularly in large geographical deployments or massive configurations, are vital in evaluating the scalability of a protocol. By analysing the quantitative scalability of nodes and geographical coverage in LEACH, it is possible to determine if the protocol maintains its performance in the context of an increase in the number of nodes or an extension of the geographical area monitored. This evaluation can answer the question of node energy management and mortality rate, highlighting the ability of the LEACH protocol to maintain these advantages in situations where both the size of the network and the area monitored vary. The in-depth analysis of scalability in the LEACH protocol, with particular emphasis on these two key dimensions, makes a significant contribution, opening up promising prospects for improvements that take account of the shortcomings identified in the LEACH protocol.

A. Research Questions

The research questions in this study focus on the following aspects.

- What are the main limitations of LEACH in terms of nodes and network energy management in very large sensor deployments?
- What are the main limitations of LEACH with regard to node and network energy management over large geographical areas?
- How does the node mortality rate evolve in scenarios where the number of sensors is significantly high?
- What are the causes of node failures in these situations?
- How does the node mortality rate evolve in scenarios where the observed geographical area is very large?

- What factors contribute to node failures in geographically large areas?
- What specific disparities exist in the load balance between clusters when considering a large number of nodes?
- How does the distribution of CHs and the geographical extent of clusters evolve at a large scale in terms of number of nodes and geographical extent?

B. Research Motivations

The research motivations in this study focus on the following aspects.

- Exploring the constraints of LEACH energy management in the context of massive sensor deployments.
- Examine the limitations of LEACH for energy management over geographically large areas.
- Understanding the evolution of the mortality rate in environments with a high density of sensors, an essential aspect for anticipating failures.
- Examine the challenges associated with the variability of the surfaces of the areas monitored, which may influence the rate of node mortality.
- Optimising the load balance between clusters, the efficient distribution of CHs, and the geographical extent of clusters is crucial to maximising the performance of a clustering protocol. Our objective is to evaluate the performance of LEACH through these three criteria.

The rest of the paper is organised as follows: the section II provides an overview of some related LEACH work, while the section III presents an understanding of the functioning of the LEACH protocol. The IV section defines fundamental notions such as the optimum number of clusters and lifetime parameters. The assumptions and parameters used in the simulations are well explained in the V section. The performances on which LEACH has been evaluated are explained in the section VI. The VII section is devoted to an in-depth analysis of the results obtained, followed by discussions aimed at explaining the performance obtained in more detail. Finally, a conclusion on our study is presented.

II. Related works

The election and determination of an optimal number of CHs in a clustering algorithm aimed at optimising energy, increasing network lifetime and balancing the number of nodes per cluster are key aspects. The LEACH protocol is one of the first and most renowned of its kind, with several strengths as well as weaknesses. These shortcomings have given rise to a number of research projects aimed at improving these weaknesses. Examples of variants known from the literature include LEACH-C [7] and MELEACH-L [8], TB-LEACH [9], ALEACH [10], LEACH-B [11], I-LEACH [12], LEACH-G [13], IB-LEACH [6], V-LEACH [14], R-LEACH [15], MLEACH [16], EMRCR [17] ,ALEACH-Plus [18], and MET-LEACH [19]. These protocols propose various approaches for selecting CHs. LEACH-C introduces a centralised algorithm, while MELEACH-L uses a backbone tree and leaders to improve energy efficiency [8]. TB-LEACH innovates by introducing a time-based selection mechanism [9]. LEACH-B focuses on cluster balancing, while I-LEACH improves the CH selection equation [12]. LEACH-G combines the centralised and distributed approaches [13], and T-LEACH introduces a hybrid CH selection [20]. Other protocols such as IB-LEACH [6], V-LEACH [14], R-LEACH [15], MLEACH [16], ALEACH-Plus [18], and MET-LEACH [19] bring specific improvements, ranging from minimising intra-cluster communication costs to introducing (Vice CH) nodes and multiple energy thresholds. Mir et all [21] have proposed a regression-based method to predict the lifetime parameters of a WSNs. Despite their contributions, these protocols have limitations, such as purely probabilistic CH selection criteria, unpredictable CH numbers, and defects related to energy and lifetime optimizations. To overcome these shortcomings, several recent works have been proposed aimed at remedying these disadvantages of LEACH, we can cite as an example the DCOPA protocol [22] [23], which is a dynamic and distributed protocol, based on a timer which introduces a competition based on a time calculated by each node of the network according to its local parameters which are the residual energy and the distance to the Base Station (BS). This dynamic protocol offers better energy management with a balanced competition, cancelling the sending of CHs announcement messages to the whole network and reducing the announcement distance to save energy. DCOPA has undergone significant improvements, namely the integration of other criteria for the election of CHs [24] and the introduction of the unequal clustering approach [25]. All the improvements mentioned above are aimed at resolving the major drawbacks of LEACH and optimising clustering performance in WSNs.

III. LEACH protocol and energy model

A. LEACH protocol architecture

LEACH is a dynamic distributed clustering protocol that is probabilistic for single-hop routing. Nodes will not need global information to elect themselves as CHs. Nodes can decide to elect themselves as CHs by comparing a value called T(i), presented in Formula 1, calculated on the basis of the percentage P of desired CHs and the number of the current round to a random number generated between [0,1]. LEACH consists of two phases: set-up and steady-state. In the set up phase, each node N(i) generates a random number between [0,1], and calculates the value of T(i) called the threshold.

$$T(i) = \begin{cases} \frac{P}{1-P*(r \bmod \frac{1}{p})} & si\ i \in G \\ 0 & \text{sinon.} \end{cases} \quad (1)$$

- P is the desired percentage of CHs calculated on the basis of the optimum number of CHs,
- r is the number of the current round.
- G is the set of nodes that were not CHs during the previous (1/P) rounds.

If the random number is less than T(i), then node N(i) becomes a CH and sends an ADV-CH message for the entire network. For the steady state phase, the nodes receiving the

ADV-CH will choose the nearest CH by sending a JOIN-CH message. The CHs broadcast the TDMA schedule for intra-cluster communication to avoid collisions. The CHs receive data from all the nodes in the cluster, after aggregation they send it directly to the BS.

B. Energy Model (Power Consumption Model)

The energy dissipation model used in the simulations is that of heinzelman et al. [7]. It accounts for transmission energy according to the size (l) of the message transmitted and the communication distance d between the sender and the receiver. Reception energy is based on the size of the message received (l), and data aggregation energy at CH level is also considered in this model. When transmitting, the energy used is defined by $E_{Tx}(l,d)$ in Formulas 2 and 3. Two different channel models and power control settings are used, depending on the distance (d), as follows:
If $(d < d_0)$, where d_0 is given in Formula 4, the channel of the free space model (d^2 power loss) and the power amplifier free space E_{fs} are employed. Otherwise, if $(d \geq d_0)$, the channel of the multipath fading model (d^4 power loss) and the power amplifier multipath E_{mp} are utilized.

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \quad (2)$$

$$E_{Tx}(l,d) = \begin{cases} E_{elec} * l + E_{fs} * l * d^2 & si\ d < d_0 \\ E_{elec} * l + E_{mp} * l * d^4 & \text{si } d \geq d_0. \end{cases} \quad (3)$$

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}} \quad (4)$$

E_{elec}, E_{mp}, and E_{fs} are defined in Table I. The reception energy $E_{Rx}(l,d)$ for l bits is specified in Formula 5, with reception being distance-insensitive.

$$E_{Rx}(l,d) = E_{Rx-elec}(l) = E_{elec} * l \quad (5)$$

The CH nodes aggregate the data (signals) with an energy called E_{DA}, see Table I, to send them to the BS.

TABLE I: Energy model parameters

Parametres	Values	Description
E_{elec}	50 nJ/bit	Required energy to run electronic circuit
E_{mp}	0.0013 pJ/bit/m^4	Multi path propagation
E_{fs}	10 pJ/bit/m^2	Free space propagation
E_{DA}	5 nJ/bit/signal	Required energy for Data aggregation

IV. Optimum number of clusters and lifetime parameters

A. Optimum Number of Clusters

The optimum number of clusters K_{opt} is computed in [7], Formula 11, as a function of the energy consumption of a CH node, a non-CH node and the energy required by a cluster and the parameters of the network and the radio. We only describe the basic steps in this paper, the complete demonstration can be found in [7]. M*M is the monitoring area, K is the number of clusters, d_{toCH} is the average distance of the CHs from the BS, N is the number of nodes.

$$E_{CH} = lE_{elec}(\frac{N}{K} - 1) + lE_{DA}\frac{N}{K} + lE_{elec}d^4_{toBS} \quad (6)$$

$$E_{Non-CH} = lE_{elec} + lE_{fs}d^2_{toCH} \quad (7)$$

$$E[d^2_{toCH}] = \frac{1}{2\Pi}\frac{M^2}{K^2} \quad (8)$$

$$E_{Non-CH} = lE_{elec} + lE_{fs}\frac{1}{2\Pi}\frac{M^2}{K^2} \quad (9)$$

$$\begin{aligned} E_{Cluster} = l(NE_{elec} + NE_{DA} + KE_{mp}d^4_{toBS} + \\ NE_{elec} + NE_{fs}\frac{1}{2\Pi}\frac{M^2}{K^2}) \end{aligned} \quad (10)$$

$$K_{opt} = \frac{\sqrt{N}}{\sqrt{2\Pi}}\sqrt{\frac{E_{fs}}{E_{mp}}}\frac{M}{d^2_{toCH}} \quad (11)$$

B. lifetime parameters

Lifetime is viewed as an key aspect in evaluating the performance of WSNs. The number of live nodes, connectivity and coverage are metrics of lifetime. QoS measurements can also be mapped to the lifetime context [26]. Several lifetime descriptions are presented in the literature [26]. In our simulations we will use the definitions concerning the number (percentage) of living (dead) nodes in the network as a function of the number of rounds.

V. Hypotheses and simulation parameters

The coverage area is M*M m^2, with N nodes distributed in a uniformly random mode, the nodes have equivalent starting energy. Two different categories of message are used, control messages and data messages. The Table II below gives a summary of the values and parameters applied. The BS is located outside the monitoring area. The simulations are made using MATLAB. We have made other assumptions about the characteristics of the network and the nodes. This set of points sets out the essential assumptions and parameters of our simulations. Firstly, it is assumed that the BS is inexhaustible in energy resources, thus making an assumption regarding its constant energy source. The nodes, statically displayed, are characterised by the non-existence of devices to identify their positions, representing an important assumption about

TABLE II: Simulation parameters

Paramètres	Valeurs	Description
$M * M$	$M^2\ m^2$	Area Network
E_{Max}	0.5 j	Initial energy
$Sink_x$	S_x m	Sink x-axis
$Sink_y$	S_y m	Sink y-axis
$MsgCtrl$	25 bytes	Control message length
$DataMsg$	200 bytes	Data message length
K_{opt}	Formula 11	Optimum clusters number [7]

their capacity. The irreplaceability of the nodes' batteries is also noted, and the failure of a node is clearly defined as the complete depletion of its energy, thus providing a clear criterion for the state of dysfunction of a node. Finally, another significant assumption is that all nodes can adjust their distance range as a function of distance from the receiver(s). In summary, these items provide a clear background for our simulations by defining the basic requirements, limitations and behaviours of the network and node types under study.

VI. Performance analysis of the LEACH protocol

A. Quantitative Scalability: Performance of LEACH in Massive Environments

In this first subsection, we undertake an in-depth study of the quantitative scalability of the LEACH protocol, focusing on its performance in massive node deployments. This analysis is of crucial importance in answering the research question on the limitations of LEACH at large scale, in particular with respect to node and network energy management. We then evaluate LEACH's ability to maintain these energy performances in massive environments. We also aim to explore the distribution of CHs and the geographical extent of the clusters constructed. By examining these aspects, we aim to identify possible limitations of LEACH and gain a deeper understanding of its performance in massive node deployment scenarios.

B. Geographic scalability: LEACH performance in Extended Environments

This second subsection focuses on the performance of LEACH in geographically extended environments, in line with the questions raised in our research motivation. We analyse how LEACH behaves when the monitored areas vary. This in-depth study aims to understand LEACH's response to geographical challenges, with a particular focus on node mortality and network lifetime. By examining the impact of geographical extent on the rate of mortality, we also seek to shed light on the distribution of CHs and identify the geographical extent of the clusters created. In doing so, we contribute to the knowledge of the performance of the LEACH protocol in scenarios of deployment in large geographical areas, aligning our analysis with the essential criteria formulated in our study and research framework.

C. Mortality rate and lifetime

To carry out our study, different scenarios are considered, covering a wide range of configurations. For the study and analysis of quantitative scalability, we vary the number of nodes deployed and a fixed geographical area. We then fix the number of nodes in the network by varying the geographical area covered. The lifetime parameters we have chosen are as follows: FND (*First Node Die*), QND (*Quarter Nodes Die*), HND (*Half Nodes Die*), SND (*Seventy-five Percentent Nodes Die*) and LND (*Last Node Die*).

VII. Simulation, results and Scalability analysis

A. Discussion on quantitative scalability

The simulations, performed by varying the number of nodes from 100 to 1000 with an increment of 100 nodes at each iteration on a $200 * 200\ m^2$ deployment surface, Table III, clearly reveal the decline in LEACH performance, in terms of lifetime parameters, as the number of nodes in the network increases, as illustrated in Figures 1 and 2. Overall, the lifetime parameters show an increasing deterioration, from an FND of 110 in a 100 nodes network to an FND of 26 with a 1000 nodes network. Similarly, the LND decreases from 651 to 249 for the same considerations. Table III clearly shows the decline in lifetime and death rate properties as the number of nodes increases.

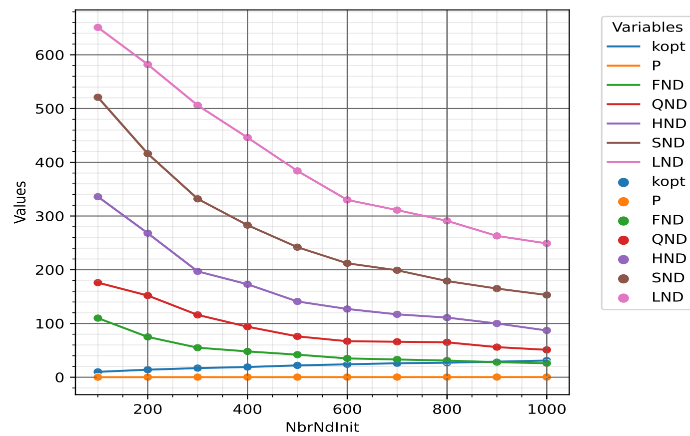


Fig. 1: Lifetime parameters by increasing the number of nodes in the network

B. Discussion on geographical scalability

The simulations were carried out by changing the size of the geographical area covered, from $100 * 100\ m^2$ to $1000 * 1000\ m^2$, with an increment of $100 * 100\ m^2$, and with a number of nodes of 300 at each iteration. In the case of a $100 * 100\ m^2$ network, we observe an FND of 452 and an LND of 876. On the other hand, for a 1000*$1000\ m^2$ network, the FND and LND both drop to 1. These results, presented in Table IV, indicate that the network can maintain its operation for a single cycle, after which it becomes completely out of order, thus exhausting its overall energy. These observations demonstrate the poor geographical scalability of LEACH, as illustrated in Figure 3.

C. Discussion on the number of elected CHs

The optimal number of CHs, denoted K_{opt}, in the LEACH protocol increases proportionally to the increase in the number of nodes or the extension of the geographical area covered, as shown by the Formula 11. However, it remains relatively small compared with the total number of nodes in the network. This is clearly seen in the simulations carried out, as shown in Table V and the results illustrated in Figure 4. The number of

TABLE III: Lifetime parameters by increasing the number of nodes in the network

Nodes	Area (m^2)	K_{opt}	P%	BS position (m, m)	FND	QND	HND	SND	LND
100	200^2	10	0.1	(100,275)	110	176	336	521	651
200		14	0.14		75	152	268	416	582
300		17	0.17		55	116	197	332	506
400		19	0.19		48	94	173	283	446
500		22	0.22		42	76	141	242	384
600		24	0.24		35	67	127	212	330
700		26	0.26		33	66	117	199	311
800		27	0.27		31	65	111	179	291
900		29	0.29		28	56	100	165	263
1000		31	0.31		26	51	87	153	249

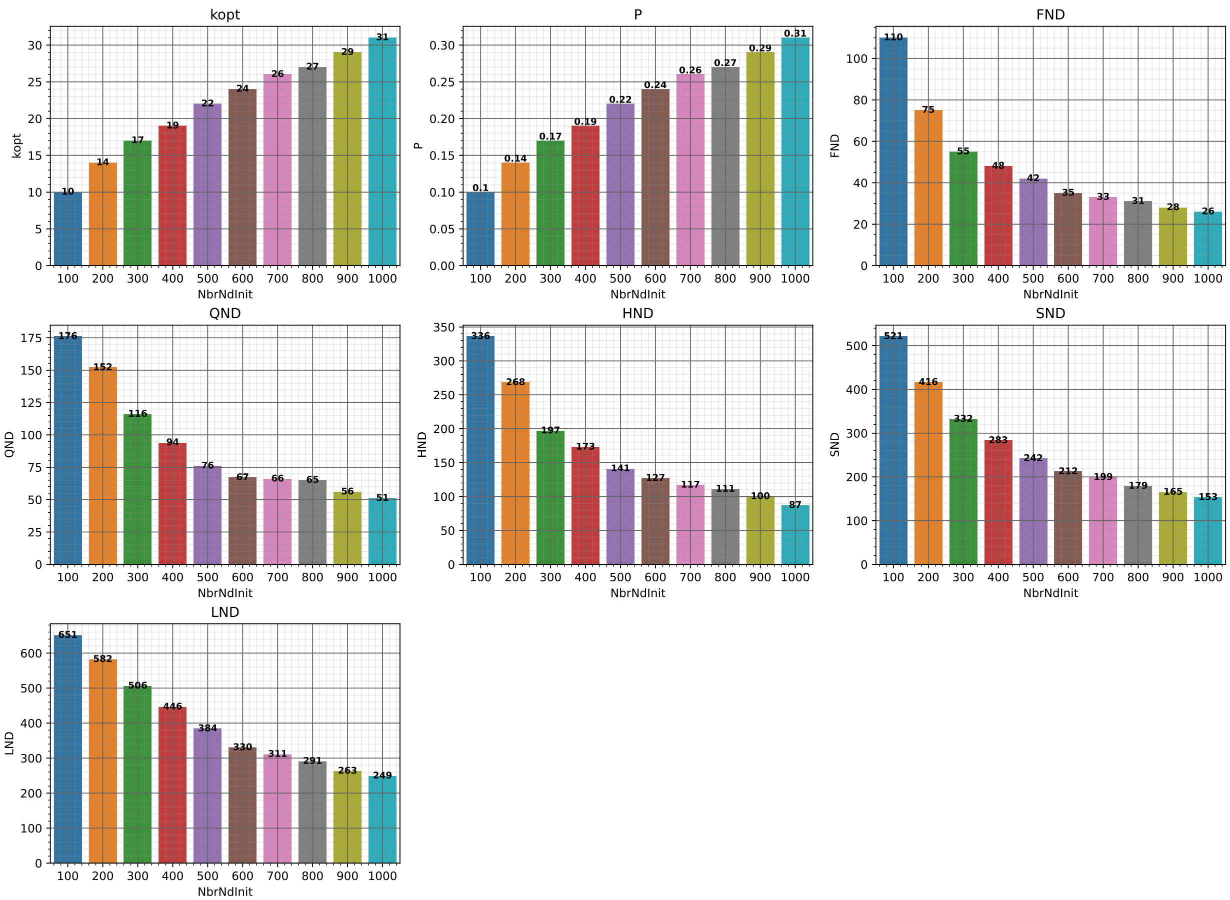


Fig. 2: Lifetime parameters by increasing the number of nodes in the network

CHs varies significantly in scenarios ranging from $100 * 100$ to $500 * 500$ m^2, involving 300 nodes. This number varies between 17 for an area of $100 * 100$ m^2 and 217 in the case of $500 * 500$ m^2. It should be noted that beyond an area of $400 * 400$ m^2, the number of CHs can exceed even the number of normal nodes, which runs counter to the initial objective of clustering.

D. Argumentation

We have of course noted that the famous LEACH protocol, known as the first clustering protocol for routing in WSNs, has several advantages. These include the distributed aspect of the protocol and the election of CHs, based on a purely probabilistic election of CHs described by a magic formula that assigns the role of CH to the nodes in the network. Despite these advantages, LEACH suffers from several drawbacks that have made scalability one of the key pillars of any clustering solution, given that sensor networks are destined to be deployed on a massive scale. Based on our simulations and analysis of the results, we find that LEACH does not provide scalability in terms of either quantity or geographical

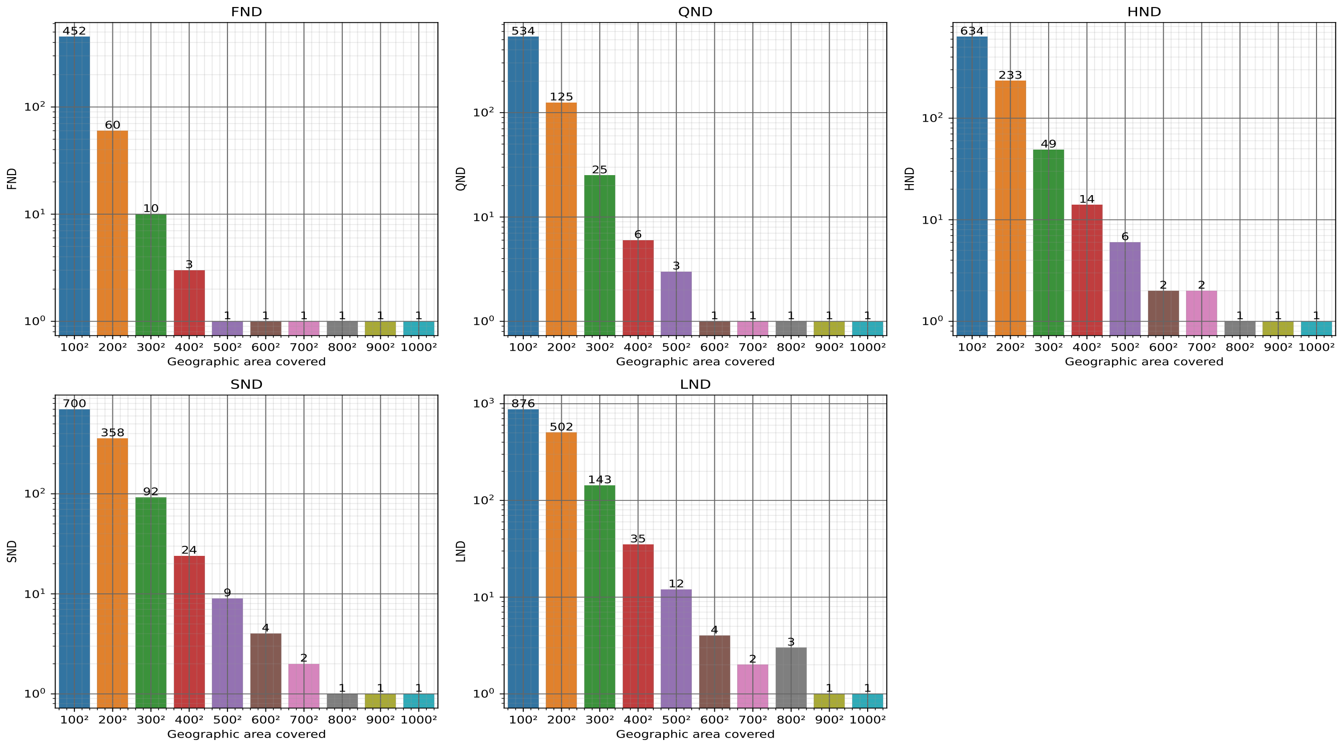


Fig. 3: Lifetime parameters by increasing the Geographic area covered

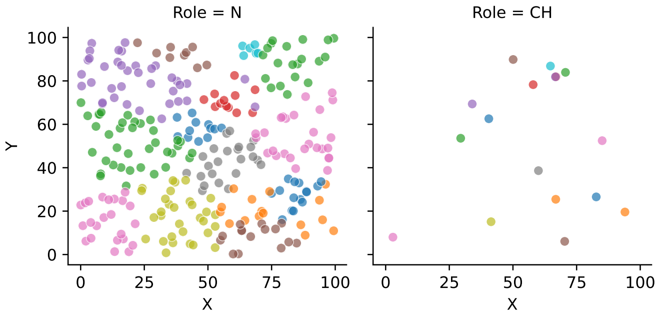
TABLE IV: Lifetime parameters by increasing the Geographic area covered

Nodes	k_{opt}	P%	BS position (m, m)	Area (m^2)	FND	QND	HND	SND	LND
300	8	0.08	(50, 175)	100*100	452	534	634	700	876
	17	0.17	(100, 275)	200*200	60	125	233	358	502
	25	0.25	(150, 375)	300*300	10	25	49	92	143
	34	0.34	(200, 475)	400*400	3	6	14	24	35
	42	0.42	(250, 575)	500*500	1	3	6	9	12
	50	0.5	(300, 675)	600*600	1	1	2	4	4
	59	0.59	(350, 775)	700*700	1	1	2	2	2
	67	0.67	(400, 875)	800*800	1	1	1	1	3
	75	0.75	(450, 975)	900*900	1	1	1	1	1
	84	0.84	(500, 1075)	1000*1000	1	1	1	1	1

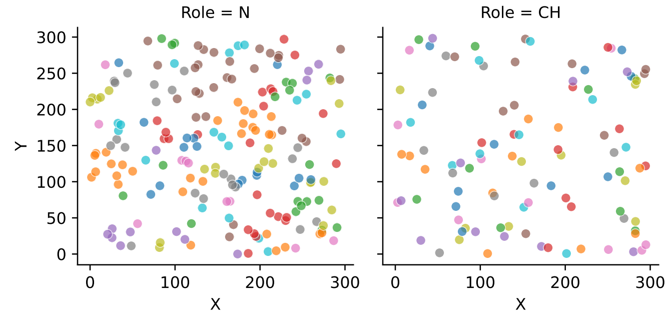
TABLE V: Number of elected CHs based on the covered area

Nodes	Area (m^2)	Number of CHs	Number of Normal Nodes
300	100*100	17	283
	200*200	70	230
	300*300	102	198
	400*400	157	143
	500*500	217	83

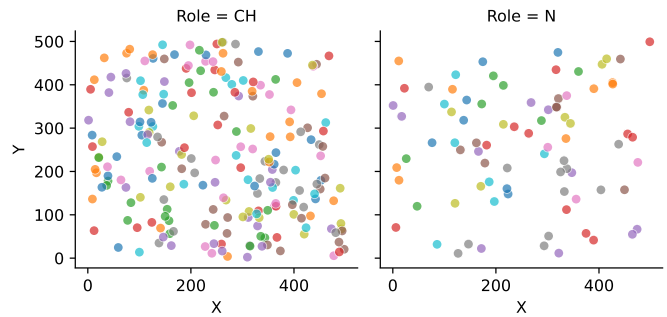
scalability. This is due to several factors, such as the random aspect of CH election, where no criteria are taken into account to determine whether a node has the possibility of being a CH or not, such as a node's energy. For example, when a CH is elected, it sends a membership message to its cluster across a radius that covers the entire network, expanding the solicitation area of normal nodes as the geographical area grows. Single-hop communication results in a significant loss of nodes communicating directly with the BS. In addition, CHs with a large number of nodes suffer from multiple receptions of control messages and data. Once the data has been aggregated, it is sent directly to the BS. The probabilistic aspect can also lead to a node being elected as a CH several times consecutively, thereby accelerating its premature failure.



(a) Area of $100 * 100\ m^2$ containing 300 nodes.



(b) Area of $300 * 300\ m^2$ containing 300 nodes.



(c) Area of $500 * 500\ m^2$ containing 300 nodes.

Fig. 4: Distribution of clusters and CHs

All these disadvantages and weaknesses of the LEACH have made scalability its major weakness.

VIII. Conclusion

Although the LEACH protocol has been hailed as the leading clustering protocol for routing in WSNs, its advantages, such as its distributed aspect and probabilistic CHs election process, are counterbalanced by significant limitations in terms of scalability. The results of our simulations and analyses indicate that LEACH fails to guarantee satisfactory scalability, both quantitatively and geographically. Major disadvantages include the randomness of CHs election, the lack of criteria considered during election (such as node energy), and the adverse effects of single-hop communication, including the significant loss of nodes directly connected to the BS. In addition, the probabilistic method of electing nodes as CHs can lead to repeated selections, thus accelerating their premature failure. These limitations are further exacerbated by the problems associated with enlarging the load area of normal nodes and receiving multiple control and data messages. All these drawbacks and weaknesses mean that scalability remains the weak link in the LEACH protocol. To meet the growing demands of massive sensor network deployments, it is becoming imperative to look for alternatives or to introduce substantial improvements to the protocol in order to ensure more efficient management of resources, a reduction in communication losses, and better adaptation to the energy constraints of the nodes.

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