# Project: Distributed Algorithm for Dynamic Network with LEACH and LEACH-C

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**Evaluation Criteria**

1. *Correct implementation of LEACH and LEACH-C protocols, ensuring proper functioning in both static and dynamic network environments.*

2. *Ability to conduct comprehensive simulations across different network configurations and scenarios, accurately capturing performance metrics.*

3. *Effective application of the energy consumption model, with clear analysis of energy efficiency for both protocols under varying conditions.*

4. *Critical evaluation of experimental results, including appropriate use of performance metrics (First Dead Node, First Muted Round, Dynamic Load Balancing Index, Relative Silence Period Index) and insightful interpretation of findings.*

5. *Clarity and organization of the final report, including well-structured presentation of results, effective use of visuals, and thorough justification of conclusions.*

**Deliverables :**

- *Python code (lien Colab) for LEACH and LEACH-C algorithms in dynamic networks with node mobility under Simpy.*

- ***Report:*** *A detailed report of 10 pages maximum containing:*
  - *Design and methodology for adapting LEACH and LEACH-C to dynamic networks.*
  - *Performance analysis based on the metrics listed above.*
  - *Comparisons between static and dynamic network simulations.*
  - *...*

**Deadline :** *5 November 2025, 23:42*

## 1 Introduction

In modern agriculture, technology plays a key role in improving efficiency and safety in cattle farming [1]. One such advancement is the use of **Wireless Sensor Networks (WSNs)** to monitor and control cattle movements and behaviors in remote and large-scale farms. These networks consist of sensor nodes attached to individual cattle, enabling real-time tracking and monitoring of vital parameters such as location, health, and environmental conditions. However, one of the critical challenges in deploying such networks is managing the energy consumption of sensor nodes, especially in dynamic environments where nodes (cattle) are constantly moving.

This project focuses on studying the energy consumption of two clustering protocols: **LEACH (Low-Energy Adaptive Clustering Hierarchy)**[3] and **LEACH-C (LEACH-Centralized)** [2]. Both protocols are designed to reduce energy usage by organizing sensor nodes into clusters, with a cluster head responsible for data aggregation and communication with the base station. By implementing and simulating these protocols in a dynamic network, where each sensor node moves randomly as the cattle roam the field, we aim to analyze their behavior in terms of energy efficiency. The study will be conducted using distributed algorithms to ensure scalability and adaptability in such dynamic settings.

# 2 Energy Model

The energy model for the simulation is based on LEACH typical energy consumption equations. The energy for transmitting and receiving data depends on the distance between nodes and the packet size. The constants are defined as follows:

```
# Energy constants in Joule (J)
E_elec = 50 * (10**(-9))  # Energy per bit for transmission/reception
E_fs = 10 * (10**(-12))   # Free-space model energy for short distances
E_mp = 0.0013 * (10**(-12))  # Multi-path fading model energy for long distances
E_da = 5 * (10**(-9))    # Data aggregation energy
```

The energy to **transmit** a packet of length $l$ over distance $d$ is given by:

$$E_{Tx}(l,d) = \begin{cases} E_{elec} \times l + E_{fs} \times l \times d^2 & \text{if } d \leq d_0 \\ E_{elec} \times l + E_{mp} \times l \times d^4 & \text{if } d > d_0 \end{cases}$$

where $d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}}$ is the threshold distance.
The energy to **receive** a packet of length $l$ is:

$$E_{Rx}(l) = E_{elec} \times l$$

The energy for **data aggregation** is:

$$E_{Ax}(l) = E_{da} \times l$$

# 3 Objective

The main goal is to implement LEACH and LEACH-C in a **dynamic cattle control network**, where each cow moves randomly in the field, and sensor nodes communicate with each other to monitor cattle health, movements, and environmental conditions. The project will focus on using distributed algorithms to efficiently manage the sensor nodes' energy consumption and ensure reliable data collection.

The static network implementation of LEACH and LEACH-C (non-distributed) for static nodes (see Figure 1) is provided at Google Colab[1].

The importance of working with dynamic networks lies in their growing relevance across various industries of the future, such as smart agriculture, logistics, and industrial automation.

[1] https://colab.research.google.com/drive/1ieFTRpC9XfmqcGze5QPsO-dbLFUFA1NV?usp=sharing

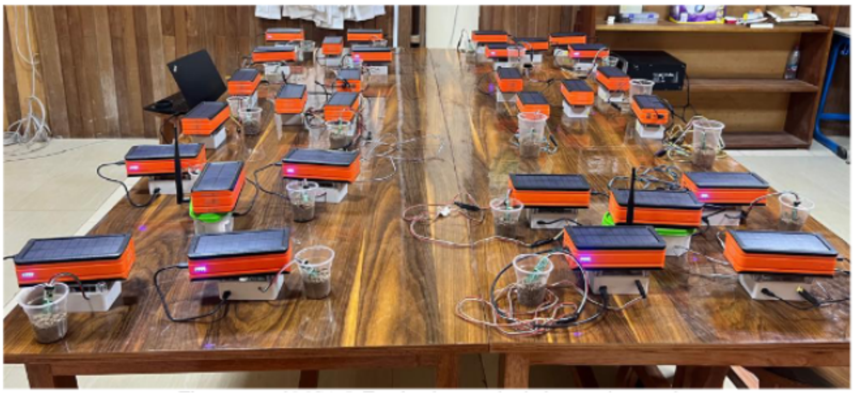

Figure 1: Smart agriculture

In these sectors, mobile entities like cattle, vehicles, or equipment are increasingly outfitted with IoT sensors to collect and transmit critical data. Unlike static networks, where nodes remain stationary, dynamic networks involve continuously moving nodes, requiring adaptive and energy-efficient protocols to ensure reliable communication and data collection. By extending this project to dynamic networks using distributed approaches, we address the challenges posed by real-world applications where mobile devices need to operate autonomously and efficiently, adjusting to changes in topology and network conditions. Such advancements are crucial for applications like precision livestock farming, where sensors attached to animals must function effectively in large, constantly changing environments as presented in Figure 2.

# 4 Project Requirements

In this project, we consider a simulation environment where cattle are dispersed across a rectangular field of dimensions **100 meters by 100 meters**. The sensor nodes, attached to each cow, are randomly distributed within this area, constantly moving as the cattle roam. To facilitate communication and data aggregation, a **Base Station (BS)** is positioned at coordinates $(0, -100)$, located outside the active field. The BS serves as a centralized data collection point, receiving information from the Cluster Heads (CHs) within the network. The goal is to ensure that the protocols (LEACH and LEACH-C) effectively route data from the nodes through the CHs to the BS, while maintaining energy efficiency. By strategically positioning the BS outside the cattle field, we model a realistic scenario where a remote station gathers and processes data from the sensor network.

## 4.1 Dynamic Network Implementation of LEACH and LEACH-C

- Extend the LEACH and LEACH-C algorithms to handle **random mobility**, where sensor nodes (attached to cattle) update their positions as the cattle move around the field.
- Implement **distributed algorithms** for cluster head (CH) election and data aggregation for efficient energy management.
- Simulate node movements and clustering behavior using `Simpy`.

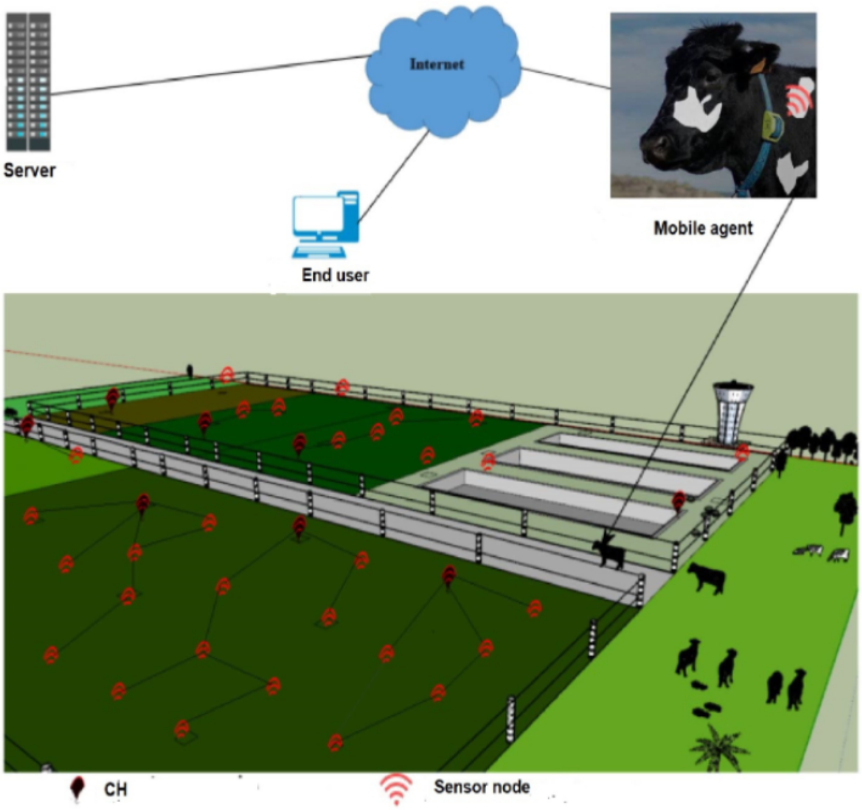


Figure 2: Cattle control

### 4.2 Experimentation and Performance Analysis

- Run experiments comparing the performance of LEACH and LEACH-C in both **static** and **dynamic** cattle control networks.
- Evaluate the behavior of these protocols using a variety of performance metrics and test with different network configurations, packet sizes, node counts (representing cattle), and user activity probabilities.

### 4.3 Simulation Scenarios

Conduct the simulation with different test parameters using the following setup:

```
(l, p, n) in [(2000, 0.05, 100), (2000, 0.5, 100), (2000, 0.95, 100),
              (4000, 0.05, 100), (4000, 0.05, 200), (4000, 0.1, 200)]
```

- **l**: represents the size of data packets sent in bits.
- **p**: is the user activity probability (likelihood of nodes sending data).
- **n**: is the total number of nodes in the network.

## 5 Performance Metrics

This project will use several metrics to evaluate the performance of LEACH and LEACH-C in both static and dynamic network conditions:

**Dead/Alive Node Count:** Tracks the number of nodes that are still operational (alive) after each round. This metric helps evaluate network longevity and energy efficiency.

**Packets to CH:** The total number of packets sent by regular nodes to their respective cluster heads (CHs) during the simulation.

**Packets to BS:** The total number of packets sent from CHs to the base station (BS). This metric reflects the efficiency of the CHs in data aggregation and communication with the base station.

**Remaining Energy:** Measures the residual energy in nodes at the end of each round. This is critical for assessing how well the algorithms manage energy consumption.

**Muted Rounds:** The number of rounds where no CH is elected, causing communication failure. Muted rounds reflect inefficiency in network stability.

**First Muted Round (FMR):** The round when the network first experiences muted communication (no active CHs). A low FMR indicates instability in CH selection.

**First Dead Node (FDN):** The round when the first node depletes its energy and becomes non-functional. FDN provides insight into network survivability.

**Last Dead Node:** The round when the last node dies, marking the end of the network's operational life. This metric evaluates the overall lifespan of the network.

**Dynamic Load Balancing Index (DLBI):** The DLBI is designed to evaluate the degree of load distribution among the active Cluster Heads within the network. CHs play a crucial role in aggregating data from neighboring nodes and forwarding it to a central base station. An uneven load distribution can lead to premature CH failure, which undermines the network stability and lifespan. The DLBI quantifies how equitably the load (in terms of data packets) is shared across CHs over $N$ rounds:

$$\text{DLBI} = \frac{1}{N} \sum_{r=1}^{N} \text{DLBI}_r \tag{1}$$

$$\text{DLBI}_r = 1 - \frac{\sum_{j=1}^{m_r} (L_{j,r} - \bar{L}_r)^2}{m_r \cdot \bar{L}_r^2} \tag{2}$$

Where $L_{j,r}$ denotes the load (number of packets) handled by CH $ch_j$ in round $r$, $\bar{L}_r$ represents the average load across all active CHs, and $m_r$ is the total number of CHs. The value of $\text{DLBI}_r$ lies in $(-\infty, 1]$ but in practice, this means the $\text{DLBI}_r$ can take on negative values, especially in cases of severe load imbalance, but it is typically designed to reflect a quality measure where $0 \leq \text{DLBI}_r \leq 1$ for well-balanced load scenarios. The DLBI can be applied to each individual round to assess the performance of the cluster head selection process, or averaged across all rounds, as illustrated in Equation 1, to evaluate the overall load balancing behavior over time.

**Relative Silence Period Index (RSPI):** The RSPI captures the network ability to maintain functional Cluster Heads throughout its operational life. Muted rounds can severely impact network performance by halting communication and leaving nodes isolated. RSPI evaluates the resilience of the CH selection algorithm by accounting for the onset of these silence periods and the overall network lifetime.

The RSPI is computed as the harmonic mean of two factors: the time until the first node becomes muted (silence begins) and the round when the last node in the network becomes inactive (network death):

$$\text{RSPI} = 2 \times \frac{\left(1 - \frac{FR_{\text{muted}}}{R_{\text{max}}}\right) \times \left(1 - \frac{LR_{\text{dead}}}{R_{\text{max}}}\right)}{\left(1 - \frac{FR_{\text{muted}}}{R_{\text{max}}}\right) + \left(1 - \frac{LR_{\text{dead}}}{R_{\text{max}}}\right)} \tag{3}$$

Where $FR_{\text{muted}}$ is the round when the first node becomes muted, meaning no active CHs are present, $LR_{\text{dead}}$ is the round when the last node becomes inactive, and $R_{\text{max}}$ is a predefined maximum round number, serving as a normalization factor.

# References


[1] Hamayadji Abdoul Aziz et al. “A collaborative WSN-IoT-Animal for large-scale data collection”. In: *IET Smart Cities* (). DOI: https://doi.org/10.1049/smc2.12089.

[2] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan. “An application-specific protocol architecture for wireless micro sensor networks”. In: *IEEE Trans. Wireless Commun.* 1.4 (2002), pp. 660–670.

[3] N. Wang and H. Zhu. “An energy efficient algorithm based on LEACH protocol”. In: *Proc. - 2012 Int. Conf. Comput. Sci. Electron. Eng. ICCSEE 2012*. Vol. 2. 2012, pp. 339–342.