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*Ηλεκτρικές & Ηλεκτρονικές Επιστήμες μέσω Έρευνας*

Master of Science By Research in
*Electrical & Electronics Engineering*

# ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

# ΠΡΩΤΟΚΟΛΛΑ ΕΝΕΡΓΕΙΑΚΑ ΑΠΟΔΟΤΙΚΗΣ ΔΡΟΜΟΛΟΓΗΣΗΣ ΣΕ ΑΣΥΡΜΑΤΑ ΔΙΚΤΥΑ ΑΙΣΘΗΤΗΡΩΝ

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
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Master of Science By Research in
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MSc Thesis

# ENERGY EFFICIENT ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS

Student: ROUNTOS, DIMITRIOS, Registration Number MSCRES-0061
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ATHENS-EGALEO, OCTOBER 2023

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## ΔΗΛΩΣΗ ΣΥΓΓΡΑΦΕΑ ΜΕΤΑΠΤΥΧΙΑΚΗΣ ΔΙΠΛΩΜΑΤΙΚΗΣ ΕΡΓΑΣΙΑΣ

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Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του πτυχίου μου».

Ο Δηλών,

Δημήτριος Ρούντος

# ΠΕΡΙΛΗΨΗ


Τα τελευταία χρόνια, έχει επιτευχθεί μεγάλη πρόοδος στα Ασύρματα Δίκτυα Αισθητήρων (WSNs). Στις περισσότερες περιπτώσεις οι κόμβοι στα WSN βασίζονται σε μπαταρίες αντί να έχουν σταθερή παροχή ρεύματος. Επίσης, σε πολλές περιπτώσεις τοποθετούνται σε σημεία με δυσχερή πρόσβαση, γεγονός που καθιστά δύσκολη την αντικατάσταση ή την επαναφόρτιση των μπαταριών τους. Λόγω αυτών των διαφόρων παραγόντων, το κύριο εμπόδιο στην υλοποίηση ενός τέτοιου δικτύου έγκειται στη μείωση της χρήσης ενέργειας για την παράταση της διάρκειας ζωής του δικτύου. Σε ένα WSN, μια σημαντική ποσότητα ενέργειας δαπανάται όταν τα δεδομένα προωθούνται μεταξύ των κόμβων ή στο Σταθμό Βάσης. Έτσι, ο βέλτιστος τρόπος για τον μετριασμό της χρήσης ενέργειας στα WSN είναι με την ενσωμάτωση στρατηγικών δρομολόγησης με εξοικονόμησης ενέργειας.

Η παρούσα διατριβή εστιάζει σε πρωτόκολλα που έχουν προταθεί για ενεργειακά αποδοτική δρομολόγηση σε WSN. Συγκεκριμένα, παρουσιάζεται αναλυτικά το πρωτόκολλο LEACH, το οποίο είναι ένα πρωτοποριακό πρωτόκολλο αυτού του είδους μαζί με κάποιους από τους διαδόχους του. Στη συνέχεια, πραγματοποιείται σύγκριση μεταξύ αυτών των πρωτοκόλλων. Για το λόγο αυτό οι δοκιμές προσομοίωσης εκτελούνται σε περιβάλλον MATLAB. Τέλος, προτείνεται ένα νέο πρωτόκολλο, που ονομάζεται TL-LEACH $_{SAS}$. Η απόδοσή του αξιολογείται συγκριτικά με αυτή άλλων παρόμοιων πρωτοκόλλων μέσω δοκιμών προσομοίωσης. Τέλος, διατυπώνονται οι καταληκτικές παρατηρήσεις.

Στο **Κεφάλαιο 1**, γίνεται μια εισαγωγή στα WSN.

Στο **Κεφάλαιο 2**, γίνεται αναλυτική παρουσίαση της ταξινόμησης των ενεργειακά αποδοτικών πρωτοκόλλων δρομολόγησης, επισημαίνοντας τις τέσσερις κύριες κατηγορίες και πολλές άλλες υποκατηγορίες.

Στο **Κεφάλαιο 3**, γίνεται μια λεπτομερής περιγραφή του πρωτοκόλλου LEACH που είναι το πρωτοποριακό πρωτόκολλο ιεραρχικής δρομολόγησης και των διαδόχων του.

Στο **Κεφάλαιο 4**, εξετάζονται τεχνικές που έχουν σχεδιαστεί σχολαστικά για να παρατείνουν τη διάρκεια ζωής και να βελτιώνουν την απόδοση των κόμβων αισθητήρων.

Στο **Κεφάλαιο 5**, πραγματοποιείται μια εκτενής έρευνα προσομοιωτή δικτύου. Συγκεκριμένα, περιγράφεται διεξοδικά η περίπλοκη ταπετσαρία εργαλείων και τεχνολογιών που στηρίζουν τις σύγχρονες προσομοιώσεις δικτύου.

Στο **Κεφάλαιο 6**, προτείνεται ένα νέο ενεργειακά αποδοτικό πρωτόκολλο δρομολόγησης. Η απόδοσή του συγκρίνεται μέσω δοκιμών προσομοίωσης με εκείνη του LEACH και ορισμένων από τους διαδόχους του.

Τέλος, στο **Κεφάλαιο 7**, γίνεται μια σύνοψη της εργασίας που εκτελέστηκε. Επιπλέον, γίνονται συμπερασματικές παρατηρήσεις ενώ παρουσιάζονται οι μελλοντικές ερευνητικές προκλήσεις.

# ABSTRACT

During past years, great progress has been achieved in Wireless Sensor Networks (WSNs). In most cases the nodes in WSNs rely on batteries instead of having a steady power supply. Also, in many occasions they are placed locations difficult to be reached, which makes it difficult to replace or recharge their batteries. Due to these various factors, the primary hurdle in implementing such a network lies in the reduction of energy usage to prolong the lifespan of the network. In a WSN, a substantial amount of energy is expended when data are forwarded between nodes or to the Base Station. Thus, the optimal way to mitigate energy usage in WSNs is by incorporating energy-conserving routing strategies.

This thesis focuses on protocols that have been proposed for energy efficient routing in WSNs. Specifically, LEACH protocol, which is a pioneer protocol of this kind along with some of its successors are analytically presented. Next, a comparison among these protocols is carried out. For this reason simulation test are executed in MATLAB environment. Finally, a novel protocol, named T-LEACH with sas, is proposed. Its performance is evaluated comparatively to that of other similar protocols via simulation tests. Finally, concluding remarks are drawn.

In **Chapter 1**, an introduction to WSNs is made.

In **Chapter 2**, a detailed presentation of the classification of the energy efficient routing protocols is performed highlighting the four major categories and many other subcategories.

In **Chapter 3,** a detailed description of LEACH protocol which is the pioneer hierarchical routing protocol, and its successors is carried out.

In **Chapter 4**, techniques meticulously designed to prolong the lifespan and enhance the efficiency of sensor nodes are examined.

In **Chapter 5,** an extensive network simulator survey takes place. Specifically, the intricate tapestry of tools and technologies that underpin modern network simulations, is thoroughly described.

In **Chapter 6**, a novel energy efficient routing protocol is proposed. Its performance is compared through simulation tests against that of LEACH and some of its successors.

Finally in **Chapter 7**, a synopsis of the work carried out is performed. Additionally, concluding remarks are made while future research challenges are presented.

# ACKNOWLEDGEMENTS

I extend my deepest gratitude to Professor Dionisis Kandris for his invaluable time, unwavering effort, accessibility, and understanding in supporting me to achieve success in my research. His immense knowledge and extensive experience have been a constant source of inspiration throughout my academic journey.

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# CHAPTER 1:
# An introduction to Wireless Sensor Networks

## 1.1. Introduction to WSNs

As it is depicted in Figure 1, a Wireless Sensor Network (WSN) consists of wirelessly interconnected devices that are called nodes, which are distributed over a certain area that is called Field Of Interest – FOI. The nodes gather data and then transmit this information to an upper-level node known as the BS or Sink Node (SN). This particular node possesses advanced processing and communication capabilities, enabling it to oversee the WSN's operations and establish communication with both the sensor nodes within the WSN and external networks or systems [1].

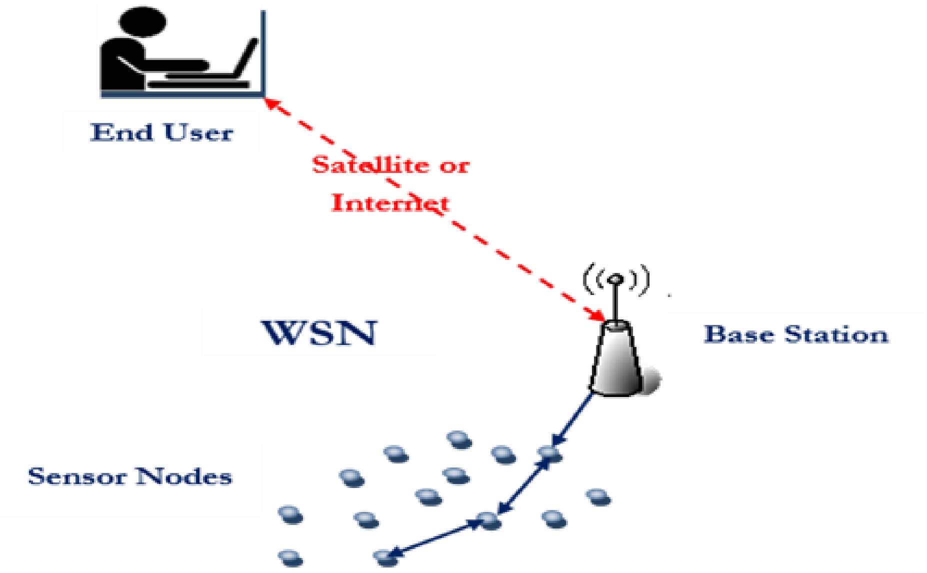


Figure 1: **Typical structure of a WSN**

In contrast to the many benefits offered by WSNs, the adoption and utilization of such networks are impeded by several challenges, which will be discussed in greater detail later in this thesis.

## 1.2. Architecture of WSN nodes

As depicted in Figure 2, the essential elements of a wireless node as a member of a WSN [1], [2] are comprised by multiple parts, that all collaborate together in order to empower the wireless sensor node to capture environmental data, process it, establish communication with other nodes, and execute specific tasks as dictated by the WSN's application:

- *Sensing Unit*: The sensing unit within a WSN node plays a crucial role in collecting data or information from the surrounding environment. WSNs consist of multiple sensor nodes distributed over an area, and each node is equipped with various components, including a sensing unit, to perform specific tasks. The core component of the sensing unit is the sensor or sensing device. These sensors can vary widely based on the application and the different varieties of data that needs to be collected. Temperature sensors, humidity sensors, light sensors, motion detectors, gas sensors, and a variety of other sensors are commonly employed in WSN nodes. These sensors are specifically engineered to gauge physical parameters or environmental conditions. The sensing unit's role is to capture environmental information accurately, efficiently, and reliably, making it a fundamental component of WSNs The selection of sensors and the configuration of the sensing unit can vary considerably to align with the specific objectives of the application.

❖ *Processing Unit*: Contains a programmable microcontroller through which it controls the entire node operations. In a WSN node, the role of this component is critical while it is responsible for managing data, executing algorithms, making decisions, and controlling the overall operation of the nodes. Here's an overview of the processing unit in a WSN node:

- Microcontroller or Processor: The central element of the processing unit is a microcontroller or processor, which serves as the "brain" of the WSN node. This component is responsible for executing program logic and managing the node's operation. The choice of microcontroller or processor is contingent on various factors such as processing power requirements, energy efficiency, and the specific application of the WSN.
- Memory: The processing unit typically includes memory components, such as RAM (Random Access Memory) and ROM (Read-Only Memory). RAM serves as a storage medium for temporary data and facilitates program execution, while ROM preserves the node's firmware or software code. Flash memory might also be used for non-volatile data storage.
- Operating System (OS) or Firmware: WSN nodes may run a lightweight operating system or firmware that provides essential functionalities, such as task scheduling, power management, and communication protocols. Some nodes may operate without a traditional OS, especially in resource-constrained environments.
- Sensor Interface: The processing unit interfaces with the sensing unit, allowing it to communicate with sensors, collect data, and control sensor operations. This interface ensures that the processor can read sensor data and manage sensor-related tasks effectively.

The processing unit plays a crucial role in transforming raw sensor data into actionable insights, ensuring efficient resource utilization, and enabling communication within the WSN. In the development of the processing unit, it's important to find a harmonious equilibrium between computational power and energy efficiency, because WSN nodes are typically deployed in resource-constrained environments, often relying on battery power.

- *Communication Unit*: A transceiver is a device, either being in a single housing or sharing a common circuit, that performs both the operation of transmitter and a receiver. The communication unit is a critical element of a WSN node, as it determines the node's ability to communicate effectively with other nodes and the central network infrastructure. The decision regarding the communication technology and protocol stack hinges on the particular demands of the WSN application, which encompass factors such as communication range, data transfer speed, power consumption, and the prevailing environmental conditions. Following is an overview of this unit in a WSN node:
    - Radio Transceiver: The core component of the communication unit is the radio transceiver. It allows the WSN node to transmit and receive data wirelessly. These components are designed to operate on specific frequency bands and communication protocols, such as Zigbee, Wi-Fi, LoRa, Bluetooth, or cellular networks, determined by the needs of the WSN application.
    - Antenna: The antenna is essential for efficiently sending and receiving radio signals. Different types of antennas, such as dipole, patch, or directional antennas, can be used depending on factors like communication range, coverage area, and directionality requirements.
    - Communication Protocol Stack: The communication unit typically includes a protocol stack that governs how data is transmitted, received, and organized within the network. These protocols ensure data reliability, address assignment, routing, and other network-related functions.
    - Communication Modes: WSN nodes can operate in various communication modes, including unicast (point-to-point), multicast (one-to-many), and broadcast (one-to-all). The communication unit must support these modes as needed by the application.
    - Energy-Efficient Communication: Considering that WSN nodes frequently rely on batteries or energy-harvesting sources, it's imperative to design the communication unit with a focus on energy efficiency. This includes techniques like duty cycling (periodic sleep-wake cycles),

adaptive transmission power control, and data compression to reduce the energy consumption during communication.

- Data Aggregation and Forwarding: Some WSN nodes act as data aggregators, collecting data from multiple nearby nodes and forwarding it to a central node or BS. The communication unit should support efficient data aggregation and forwarding mechanisms.

❖ *Power Unit*: This part supplies the essential power to the node, with a battery being the common choice in most instances. Power management is crucial in WSNs because sensor nodes are often deployed in areas hard to be approached while their energy sources are limited.

The power unit is essential for ensuring the long-term reliability and sustainability of WSN nodes. Efficient power management strategies are critical in WSNs, as they directly impact the node's operational lifetime, maintenance requirements, and overall cost-effectiveness. Different WSN applications may have varying power requirements and constraints, and the design of the power unit should be tailored accordingly.

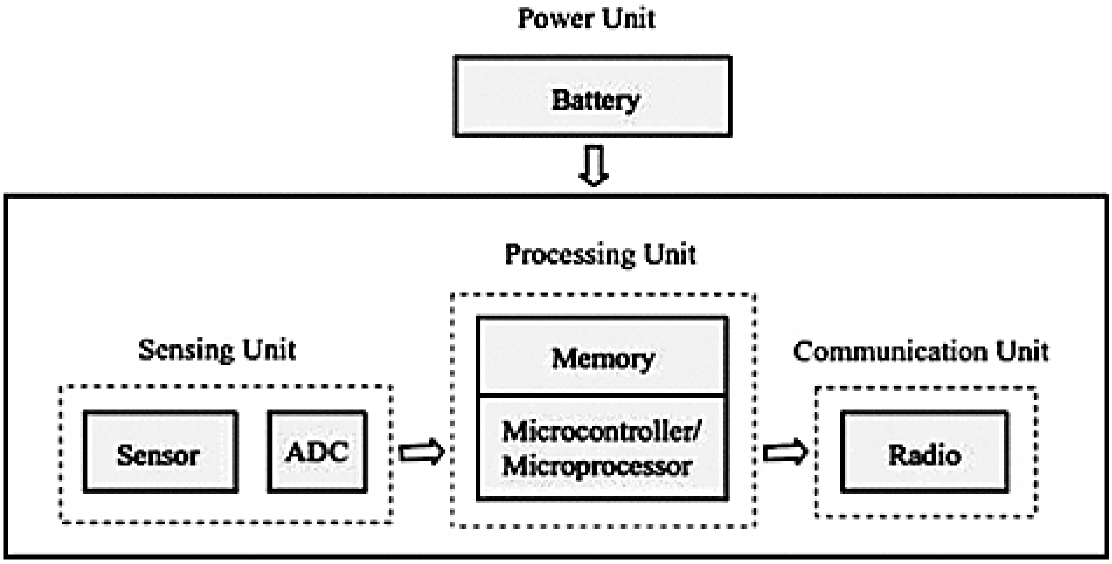


**Figure 2**: The primary elements of a wireless sensor node

Additionally, units for position tracking and mobility may be incorporated in order to enhance the network's capabilities. These additional features can provide more comprehensive and dynamic data collection and control within the network.

## 1.3. Applications of Wireless Sensor Networks

As mentioned earlier, the initial deployment of WSNs took place during the Vietnam War. Nevertheless, in the present day, WSNs are witnessing a continually expanding range of applications [2], covering areas , like battlefield surveillance, unmanned aerial vehicles

(UAVs), border security [3], environmental such as weather forecasting , air quality monitoring or forest fire detection [4], flora and fauna, such as pest control, livestock monitoring or precision agriculture [5], health such as remote patient monitoring, fall detection, or hospital asset tracking [6], industrial like condition monitoring, supply chain management , or oil and gas industry [7], and various urban sectors of human activity [8], [9], such as traffic management for smart cities, waste management, public safety and so on.

Figure 3 depicts the main categories of the applications of WSNs.

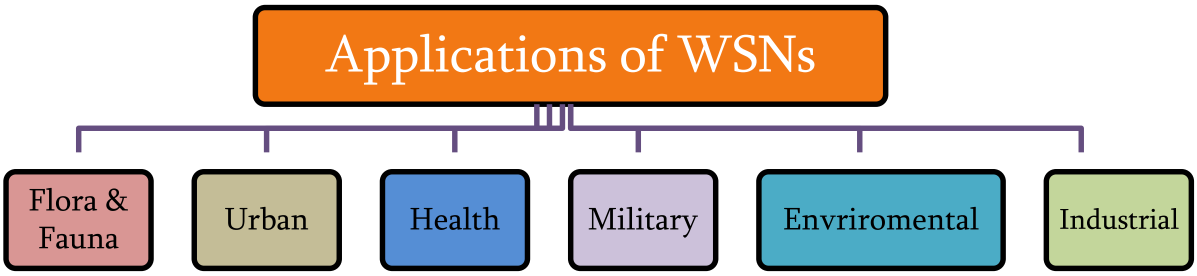


**Figure 3**: Applications of WSNs.

## 1.4. Traffic Patterns in Wireless Sensor Networks

The study of data traffic in WSNs is crucial for optimizing network performance, energy efficiency, and ensuring the successful operation of the network. A traffic pattern in a WSN refers to the way data is generated, transmitted, and received by sensor nodes within the network. Understanding and analyzing traffic patterns is crucial for designing efficient WSNs and optimizing their performance. Traffic patterns within a sensor network can exhibit significant diversity, contingent on the application and the unique prerequisites of the network. This traffic can be classified as either single-hop or multi-hop.

Single hop traffic refers to data transmissions that occur between two devices in direct radio communication range of each other without the need for intermediate relay nodes. In a single-hop scenario, data are forwarded directly from the initial node to the destination node.

The multi-hop traffic is used when the distance between sensor nodes and the sink node is greater than the communication range of individual nodes. Data is relayed from node to node until it reaches the sink node. As depicted in Figure 4, multi-hop traffic can be classified into the following patterns [10]:

a. *Local communication*: Often referred to as short-range communication or proximity communication, involves data transmission between devices or nodes that are in close physical proximity to each other. This type of communication is typically limited to a short range, and it is often used for various purposes, such as sharing information, synchronizing devices, or enabling collaboration in close quarters.

b. *Point – to – point*: Involves data exchange between two specific devices or nodes. It is a communication model where data flows from a single sender to a single receiver.
c. *Convergence*: Multiple data flows or communication paths come together or converge onto a common destination or point.
d. *Aggregation*: Data packets originating from multiple nodes are combined and forwarded as a unified packet to a designated CH or BS.
e. *Divergence*: Messages or queries from the SN or the BS are transmitted back to the nodes

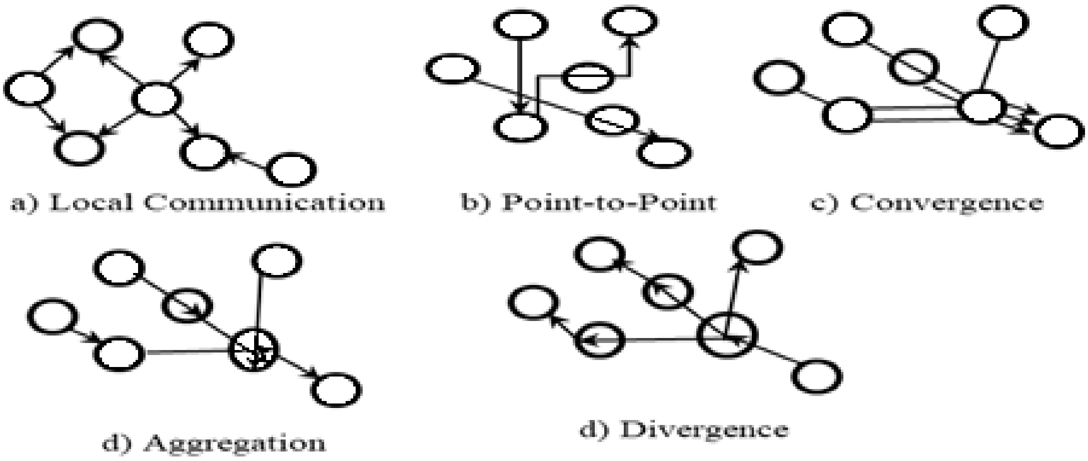


**Figure 4**: Traffic patterns specific to WSNs.

Analyzing these traffic patterns is essential for optimizing various aspects of WSN operation, including routing protocols, energy management strategies, and network design. By understanding the traffic patterns, the WSN can be tailored so all the requirements should be fulfilled while conserving energy and prolonging the network's lifetime.

## 1.5. Problems of Wireless Sensor Networks

It is commonly accepted that WSNs despite their great capabilities, they face numerous problems that affect their operation by causing serious malfunctions that can lead to network collapse.

For example, WSNs are particularly susceptible to security threats because they often consist of large populations of dispersed nodes, which can potentially serve as entry points to the network for malicious intruders [11].

Furthermore, congestion is a more common occurrence in WSNs compared to wired networks, often resulting from interference or buffer overflow [12]. It occurs when the traffic within the network exceeds the network's capacity to efficiently process and transmit that traffic. This can result in a variety of problems, including increased packet loss, delays in data transmission, and a potential negative impact on network performance.

Congestion in WSNs can stem from a range of factors, and its resolution is crucial for upholding the reliability and effectiveness of the network [13].

Loss of connectivity is a prevalent issue in WSNs, primarily stemming from the distinctive features and limitations inherent to these network structures. On the other hand, the goals of attaining maximum coverage and/or k-coverage have to be fulfilled. Therefore, specialized control mechanisms must be employed to address this issue [14] [15], [16].

Attaining high Quality of Service (QoS) is indeed crucial in various communications and networking scenarios, including WSNs. QoS refers to the overall performance characteristics of a network or communication system, such as reliability, latency, throughput, and efficiency. However, achieving this objective is challenging due to the inherent issues in wireless communications. This necessitates the utilization of specific routing protocols [17]. Moreover, when dealing with multimedia data, control mechanisms need to be implemented. [18], [19], [20].

Last but not least, the most significant problem in WSN, with the greatest impact is the extremely short lifetime of the battery. The lack of energy implies with loss of communication between nodes, including base node, loss of data packets and at the end, network collapse. [21] This limitation underscores the importance of creating protocols with better performance regarding the energy efficiency together with mechanisms to prolong the network's operational lifespan.

Extensive research endeavors are ongoing to determine the most efficient routing protocol regarding the energy consumption issues. These initiatives are geared towards optimizing the network's longevity, curbing energy usage, and enhancing the overall dependability and effectiveness of WSNs.

Strategies like duty cycling, data aggregation, energy harvesting, and efficient routing are employed to mitigate the consequences of short battery life and make WSNs more practical and sustainable in various applications [22].

However, the major factors that affect the lifetime of WSN can be focused on:

a. *Scalability*: Scalability is a critical consideration in WSNs as these networks may be differentiated in size, from small-scale deployments to large-scale networks with thousands of sensor nodes. To ensure the efficient operation of WSNs at various scales, appropriate routing protocols are essential.

b. *Mobility*: Unlike traditional WSNs where sensor nodes are typically stationary, mobile WSNs involve nodes that can move, and they are designed to address specific challenges and applications.

c. *Energy* constraint is indeed one of the most significant and demanding limitations in WSNs. Sensor nodes in WSNs are often use batteries as source of energy or energy harvesting mechanisms, and they have finite energy resources. Managing and optimizing energy consumption is crucial for the successful operation and longevity of WSNs.

d. *Positioning of BS*: The positioning of the BS is a critical consideration in the design and operation of a WSN. The BS is the demarcation point for data collection and communication with the sensor nodes and forwards this data to the outer world and its location can have a significant impact on network performance.

## 2.1. Introduction

Energy-efficient routing protocols are fundamental in Wireless Sensor Networks because they directly impact the energy consumption of sensor nodes. Given that sensor nodes in WSNs are often use battery as energy source and have limited energy resources, it's crucial to design routing protocols that minimize energy consumption while effectively delivering data to the desired destinations.

These protocols can be categorized into four major groups and several other sub-categories based on their approaches and techniques. [22] [23], as it is shown in the figure 5:

a. Classification based on communication model
b. Classification based on network structure model
c. Classification based on topology
d. Classification based on reliable routing

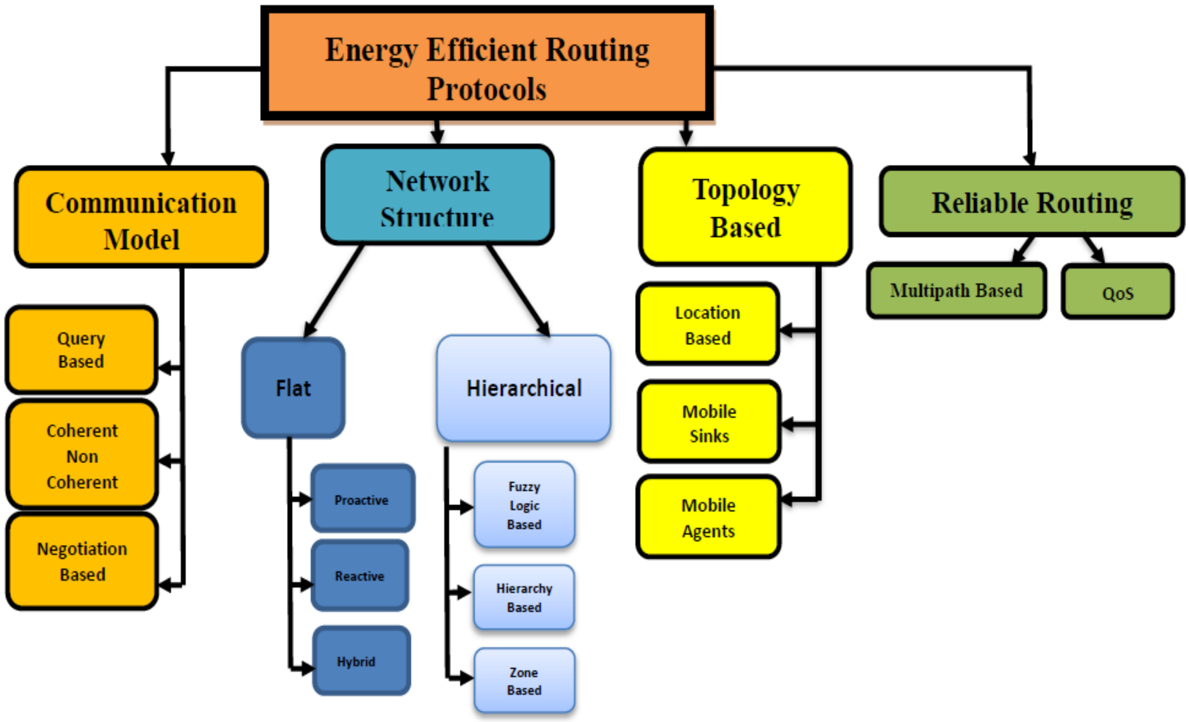


**Figure 5:** Categorization of Energy Efficient Routing Protocols in WSNs.

More precisely, the energy-efficient protocols categorized within the Communication Model group are associated with the manner in which the protocol's fundamental function is carried out for routing packets within the network.

Within Network Structure protocols, the primary distinguishing factor revolves around whether a hierarchical structure exists among the network nodes or not. Topology-based routing protocols in WSN utilize the network's structural data to make informed routing decisions. These protocols leverage the network's topology to identify the most efficient data transmission path.

Finally, the protocols the Reliable Routing protocols are essential to ensure the dependable delivery of data, especially in applications where data accuracy and integrity are critical.

## 2.2. Protocols based on Communication Model

Depending on the method by which nodes exchange data, the protocols of this category can be further divided into subcategories:

a. Query – Based,
b. Coherent & Non Coherent and
c. Negotiation – Based

### a. Query – Based Protocols

These routing protocols perform data routing according to queries made. The destination nodes propagate queries among to the target nodes. The target nodes, reply to these queries and send back the required information. These protocols are designed to optimize energy consumption by only transmitting data that is explicitly requested, rather than periodically sending data. Query-based protocols are often used in applications where energy efficiency is a critical concern. [24]

Next, some popular query-based protocols are presented.

i. *Directed Diffusion Protocol (DD):* In this protocol the nodes are application-aware. For energy consumption savings purposes, DD protocol tries to discover the low cost routes while fast memory techniques and processing data in the network are used [25].
ii. *COUGAR Protocol*: This protocol behaves as if the network is a large distributed database. This protocol introduces a new level – query level between network and application layer. All required queries functions are executed in this new level. [26]

Query-based protocols enable WSNs to function with enhanced efficiency by transmitting data solely when necessary, contributing to energy conservation and to extend the network's lifespan. The selection of a protocol is contingent upon the specific demands of the application and the intended balance between energy efficiency and query adaptability.

### b. Coherent & Non Coherent based Protocols

Coherent and non-coherent protocols describe the level of synchronization required for reliable data transmission.

Within coherent routing, aggregator nodes receive the data packets forwarded by the sensor nodes and engage in additional data processing. Coherent protocols demand precise synchronization between the sender and receiver to ensure successful data transmission. In coherent systems, the receiver must be able to accurately track the phase and frequency of the received signal to demodulate and decode the information correctly.

Coherent communication is typically used in scenarios where there is a strong and stable carrier signal, making synchronization feasible. Some of the coherent protocols are the following: [27].

i. High data accuracy and reliability.

ii. Better performance in environments with low noise and interference.

iii. Suitable for long-range communication.

In non-coherent routing, data processing takes place locally at the nodes, and these nodes subsequently transmit the processed data to other sensor nodes or cluster-heads. A typical coherent protocol is the *Multiple Winner Algorithm (MWE).* It is a typical example of coherent-based energy efficient routing protocols. To conserve energy, the quantity of nodes capable of transmitting data is restricted. As a result, instead of retaining records for only the most optimal candidate node, each node maintains a record of all potential candidates. Consequently, the Minimum Weighted Energy (MWE) approach allows each sensor node to have a collection of minimal energy paths to every other sensor node. [28]

Non-coherent protocols, in contrast, do not mandate precise synchronization between the transmitter and receiver. In these protocols, the receiver does not need to accurately track the phase and frequency of the incoming signal. Instead, it relies on techniques like energy detection or differential modulation to detect and demodulate the transmitted data.

Some of the advantages of non-coherent protocols are presented below:

i. Reduced complexity and energy consumption compared to coherent systems.

ii. More robust in environments with significant noise and interference.

iii. Suitable for short-range or low-power communication scenarios.

In WSNs, where sensor nodes often operate with limited computational resources and are deployed in challenging environments, non-coherent protocols are sometimes preferred because they can perform reasonably well in the presence of noise and interference without the need for precise synchronization. [29]

An example of a protocol within this category is the Single Winner Algorithm (SWE), in which the elected node, known as the Central Node (CN), serves as the aggregator. The selection of this node is determined by the energy level it possesses. [28].

The choice between coherent and non-coherent protocols depends on various factors, including the specific application requirements, available hardware, and the trade-offs between complexity, energy consumption, and communication performance. In scenarios where synchronization is challenging or resource constraints are significant, non-coherent protocols may be a more practical choice.

#### c. Negotiation – Based Protocols

Negotiation-based protocols in WSNs are a category of communication protocols that involve negotiation between sensor nodes or between nodes and a sink node or user. These protocols enable nodes to exchange information, make decisions collaboratively, and optimize communication based on specific negotiation strategies.

These types of routing protocols are based on two main ideas:

i. In order the protocol to be energy conservative, all nodes should communicate each other and to exchange information about the received and required data.
ii. All nodes that participate in a WSN should track and record the available energy repositories and to be adjusted accordingly.

*Sensor Protocols for Information via Negotiation (SPIN):* This protocol's primary feature is its utilization of metadata to minimize redundant routing transmissions. When a node possesses new data, it broadcasts an ADV packet to inform other nodes. If a node expresses interest in this data, it replies with a request packet, prompting the original node to transmit the data. Many new versions have been developed based on SPIN, like:

- SPIN with Energy Consumption (SPIN-EC) [30]
- SPIN for Point-to-Point Communication (SPIN – PP) [30]
- SPIN for Broadcast Networks (SPIN – BN) [30]
- SPIN with Reliability (SPIN – RL) [30]

## 2.3. Protocols based on Network Structure

Protocols in this category can be further categorized in two subcategories based on the way they introduce a node in a wireless network. In small wireless networks with no expansion capabilities and short node number, all nodes have the same importance, but in most of the cases the nodes have different roles between them.

The two subcategories are:

a. Flat Routing Protocols and
b. Hierarchical Routing Protocols

#### a. Flat Routing Protocols

All nodes that participate in the same wireless network are equal to each other. These protocols can be further categorized based on the routing strategy into three fundamental categories: [31]

i. Pro-active,
ii. Re-active and
iii. Hybrid Protocols

**i. Pro-active Routing Protocols**

In this subcategory of protocols, there is often a periodic exchange of routing tables among nodes to ensure they have a well-informed understanding of the network's topology. Following, some indicatives pro-active routing protocols are presented.

a. *Wireless Routing Protocol (WRP):* The Wireless Routing Protocol – WRP [32]– uses routing table. Each node in the network contains the following tables:
   - The Distance Table having information for the adjacent nodes of a node x.
   - The Routing Table of node x keep tracks of the paths and it is used in order to determine which path the node x will use in order to forward the data packets.
   - The Link-Cost Table refers to the relative communication costs between nodes.
   - The Message Retransmission List (MRL) has a list of nodes adjacent to node x, to which its messages have not been acknowledged.

In case of a connection loss, this protocol contains a constantly updated instant of the network and can provide a quick decision for an alternative routing path.

b. *Global State Routing (GSR):* Neighbor nodes are exchanging among themselves information (vector link- state). With this information, nodes retain a "comprehensive" perspective of the network's topology, enabling them to identify the most efficient path to the destination. [33]
   Each node keeps:
   - A Neighbor List, which contains the nodes which are near to node x and the distance between them is one hop.
   - A Topology List, which consists of two parts: the link state information and the timestamp.
   - A Next Hop, which refers to the next closest node the data packets, should be forwarded.
   - A Distance table which contains the shortest distance to each destination node.

**ii. Re-active Routing Protocols**

These protocols are on demand routing protocols. When a node intends to send data to the BS or a SN, it only initiates the routing process at that moment, seeking to identify the route leading to its intended destination. Some of the common used re-active routing protocols are discussed.

a. *Temporary Ordered Routing Algorithm (TORA):* TORA protocol doesn't reserve any routing table but instead, the nodes are classified based on their height. In this context, "height" refers to the separation between a given node and the BS. The greater the distance between a node and the

BS, the greater its height value. Data is consistently relayed from nodes with higher height to those with lower height. The protocol encompasses three core functions: route creation, route maintenance and route erasure [34].

b. *Signal Stability Routing (SSR):* This routing protocol utilizes signal strength between nodes as a criterion. SSR operates based on the use of two tables, the Signal Stability Table (SST), that contains the signal strength of adjacent nodes and the Routing Table (RT) that contains information about the next node the data will be forwarded. SSR encompasses two cooperative protocols which are: the Dynamic Routing Protocol (DRP) and the Static Routing Protocol (SRP) in order to route data. Specifically, SRP executes the actual RT lookup to forward data to the next hop while DRP updates automatically the path between the nodes, based on the network changes. [35]

#### iii. Hybrid Routing Protocols

Protocols within this subcategory amalgamate the advantages of both proactive and reactive routing protocols. Specifically, routing is primarily set up with proposed routes that have been discovered in proactive manner and then on-demand method is used from additional nodes that have been activated through reactive flooding. [36]

Some of the most common hybrid protocols are described below.

a. *Zone Routing Protocol (ZRP):* The Zone Routing Protocol, divides the network in zones. A zone radius ρ and contains all the nodes whose distance from the reference node is equal to ρ. In ZRP, each node retains routing information only for the nodes that belongs into the same zone. With this way the data packets are forwarded into local level using IARP – Intrazone Routing Protocol. For forwarding packets outside of the zone, the IERP – Interzone Routing Protocol is used. [36]

b. *Stable – Link Zone Routing Protocol (SL-ZRP):* The Stable – Link Zone Routing Protocol is an enhanced version of ZRP aiming to guarantee link stability in Internet of Vehicles. It considers three factors: node priority, node speed and node delay. [36]

### b. Hierarchical Routing Protocols

These protocols use the term "*cluster*". The cluster is the head node in a certain area. The cluster's responsibility is to communicate only with the nodes that are in the same area and exchange messages only to other clusters or to base node, when it is triggered. Overall, clustering is a fundamental technique in WSNs for improving energy efficiency, data management, and network scalability. The choice of clustering algorithm and cluster management strategy depends on the specific requirements and constraints of the WSN application.

The usage of such protocols has many advantages because the length of the routing table is decreased and has better scalability.

These protocols can be further categorized into three subcategories:

i. Hierarchy Based Protocols

ii. Fuzzy Logic Based Protocols and

iii. Zone Based Protocols.

#### i. Hierarchy Based Protocols

Probably this is the most popular subcategory of energy efficient routing protocols. Below are described some typical protocols of this subcategory. Especially for the LEACH protocol a chapter is dedicated to it.

a. *Low-Energy Adaptive Clustering Hierarchy (LEACH):* The LEACH protocol operates on a hierarchical basis, creating clusters determined by signal strength, and employing CHs for aggregation, compression and transmission data to the BS [37]. LEACH employs a randomized selection process to designate nodes as CHs, considering their signal strength. It subsequently rotates the CH role to different nodes, ensuring an equitable distribution of power levels among the nodes. The primary advantages of the LEACH protocol are its energy-efficient characteristics, which make it conducive for conserving energy among the nodes and extending the network's lifespan. Numerous studies and research efforts have been built upon the LEACH protocol, leading to the creation of various protocol variations, like:
   - MODLEACH: (Modified Leach) [38]
   - MODLEACHHT: (Modified Leach with hard threshold) [38]
   - MODLEACHST: (Modified Leach with soft threshold) [38]
   - LEACH - C : Low Energy Adaptive Clustering Hierarchy Centralized [39]

b. *Threshold sensitive energy efficient sensor Network (TEEN):* This protocol is designed for unstable situations in a network, like temperature changes [40]. In this protocol, terms hard threshold and soft threshold are used. The first term is defined as an upper value when as soon as it exceeds, the node switches on its transmitter and reports this incident to the CH. The second term denotes a slight alteration in the measured attribute's value, which prompts the node to activate its transmitter and initiate transmission. When a parameter reaches the hard threshold for the first time, the node sends the data which are tracked. The tracked value of the data is stored locally in a variable in the node which is called sensed value. The advantage of TEEN protocol is that can be used when the network is dealing with sudden ambient changes. This feature made TEEN is considered as one of the most well-known protocols of this type.

c. *Scaling Hierarchical Power Efficient Routing (SHPER):* It is a hierarchical energy efficient protocol [41] that consists of two phases. During the initial phase, the BS transmits a TDMA signal to all nodes in certain timeslot for each node. The nodes, respond to this signal and based to the strength of the respond signal, their in-between distances are identified. After that, the BS elects randomly from the nodes which has received the advertising message to be high level CHs and from the other nodes which have not received any message to be the low level CHs. High level CHs are located closest to BS and can communicate through one hop distance, while low level CHs should always communicate to BS through high level CHs. SHPER uses thresholds similarly to TEEN. In each cluster, the node that has the maximum residual energy is elected as the CH. Also, the route selection policy proposed by SHPER considers, for all possible paths, not only the residual energy of nodes but also the overall energy consumption that is caused in every routing path. In this way, data routing is carried only via the paths that cause the overall minimum energy expenditure within the network. That is why SHPER performs better than both LEACH and TEEN. A modified version of SHPER, named PEMuR, has been proposed in order to be used in Wireless Multimedia Sensor Networks {WMSNs) [42].

**ii. Fuzzy – logic Based Protocols**

These families' protocols combine fuzzy logic techniques along with efficient network operation. Below some of the most representative protocols of this category are described.

a. *Fuzzy – Logic TEEN (FL-TEEN):* This protocol uses a fuzzy logical approach to elect CH and it is based on three variables: Battery Level, Node Density & Data Frequency. The Battery Level indicates the availability of a node, the Node Density indicates the number of adjacent nodes and the Data Frequency is the number of the data which are defined by the two thresholds in previous rounds. [43]

b. *Fuzzy – logic Based Energy Efficient Packet Loss Preventive Routing Protocol (FEEPRP):* This protocol uses a fuzzy logic technique in order to discover a route between nodes with the minimum packet loss ratio because of some factors like congestion, nodes intrusion and attack, etc. It also uses a fuzzy logic control system in order to assure QoS and security between the nodes. [44]

#### iii. Zone Based Protocols

These protocols segment the network into zones. Each zone can contain cluster and CH or without CH. For each zone can be assigned a certain level of energy power depending on the protocol or certain number of nodes which transmit data from the zone to the BS. A typical example of the zone – based protocol is presented below.

*Zone – Based Energy Aware data CoLlection (ZEAL):* This protocol divides the network into three zones:

- Mobile – sink nodes, which collect the data from the sub – sink nodes,
- Sub – sink nodes, which receive the data from the nodes and forward it to the Mobile – sink nodes.
- Member nodes, which forward the data to the Sub – sink nodes. [45]

## 2.4. Protocols based on Topology

These protocols rely on the principle that every node within a network retains topological information. These protocols can be additionally categorized into the following subgroups:

a. Location – Based Routing Protocols,
b. Mobile – Sinks Protocols and
c. Mobile – Agents Protocol

#### a. Location – Based Routing Protocols

These protocols are often known as geographic routing protocol or position based routing protocols. There are based on the following assumptions:

- Each node is informed about the location of the adjacent nodes.
- The message source should be informed about destination location.

The following describes some of the typical protocols in this subcategory.

a. *Distance Routing Effect Algorithm for Mobility (DREAM):* A crucial feature of this protocol is that each node possesses its geographic coordinates, typically obtained through GPS. These coordinates are shared among nodes and stored in a routing table. The benefit of this protocol is that nodes are only required to exchange location information, rather than transmitting complete data packets. [46]

b. *Scalable Energy – Efficient Location – Aided Routing (SELAR):* The neighbor nodes, which use this protocol in order to communicate each other, exchange only information about where are located and about their energy level. In this way, every node forward the data packets, according to the available level of energy resources. [47]

**b. Mobile – Sinks Based Protocols**

Mobile – sinks are often used instead of static sinks in order to eliminate problems that occurred by static sinks, like hot – spot problem, high latency and high energy consumption. Mobile sinks-based protocols are designed to optimize data collection and communication when mobile sink nodes (e.g., vehicles or drones) are used to collect data from static sensor nodes located in the field.

Some typical protocols of this subcategory are described below:

a. *Mobile – sink based adaptive Immune Energy – Efficient clustering Protocol (MSIEEP):* This protocol uses adaptive immune algorithm in order to guide the mobile – sinks across the networks. Furthermore, this algorithm is employed to enhance both the network's lifespan and its stability period. [48]

b. *Mobile – sink based Routing Protocol (MSRP),* are designed for WSNs where the sink node (the BS or the mobile sink) is mobile rather than stationary. These protocols are particularly useful in scenarios where the sink node needs to move to different locations within the sensor network to collect data efficiently. [49] Mobile sink-based routing protocols are essential for applications where the sink needs to be mobile for reasons such as data gathering from various locations, improved data freshness, or energy efficiency. These protocols are specifically engineered to adjust to the ever-changing network topology and effectively route data to mobile sinks while ensuring reliability.

**c. Mobile – Agent Based Protocols**

This class of routing protocols uses mobile agents (software entities) for gathering data from sensor nodes. These mobile agents can move through the network autonomously, collect data, and perform various tasks. Mobile Agent-Based Protocols are especially useful in scenarios where data collection efficiency, energy conservation, and adaptability to network dynamics are essential, such as in environmental monitoring, disaster response, or surveillance applications.

In what follows some protocols of this subcategory are mentioned.

a. *Near Optimal Itinerary Design Algorithm (NOID):* This protocol utilizes multiple mobile agents that independently travel through flat networks in order to gather and aggregate data. This improves the parallelism of data aggregation routing that subsequently lessens delay. In this way, data aggregation delivery time is reduced [50].

b. *Tree-Based Itinerary Design (TBID)* exploits a quantity of spanning trees (SPTs) in order to combine and report data in zoned networks. SPTs are established from the single-hop neighborhood of sink. Then, a mobile agent is assigned to each individual SPT for data aggregation [50].

## 2.5. Protocols based on Reliable routing

These protocols are often used in networks with multiple routes or when it is required to fulfill some QoS parameters, like delay, energy or available bandwidth. The nodes of this network can suffered from the maintenance of the routing tables and QoS metrics in sensor nodes.

These protocols can be derived in further categories, like below:

a. Multipath–Based Protocols and
b. QoS – Based Protocols.

### a. Multipath – Based Routing Protocols

The protocols of this kind use load balancing techniques and they exhibit greater resilience in the face of route failures. These protocols are used especially in large scale WSN. The aim is the discovery of multiple bidirectional routes between each sensor node and the BS.

Below are some typical examples of this subcategory:

a. *GRAdient Broadcast (GRAB):* It focuses on efficient and reliable data dissemination from a source node to multiple destinations within the network. GRAB employs a gradient-based approach to establish data dissemination paths and is particularly well-suited for scenarios where data has to be reliably distributed to various nodes in the network [51]. Based on GRAB protocol, new algorithms have been presented in [52] called P-GRAB (Probabilistic – GRAB) and in [53] U-GRAB (Utility – GRAB) was introduced.

b. *Routing Protocol for Low power and Lossy Networks (RPL)* is an IPv6 protocol that can rapidly generate network routes, share routing knowledge and adjust the topology effectively [54].

### b. QoS –Based Routing Protocols

These are designed to prioritize and optimize network performance according to specific quality of service requirements. These protocols consider factors such as data reliability, latency, throughput, and energy efficiency to meet the needs of various applications [55]. To ensure QoS in the network when transmitting data to the BS, several criteria must be met, i.e. delay, energy consumption, bandwidth, and more.

The most popular protocols of this category are:

a. *SPEED Protocol:* SPEED is known for its efficiency and low energy consumption, making it suitable for resource-constrained sensor nodes and it is used for real time communication [56].
b. *Multimedia Geographic Routing (MGR):* This protocol is designed to conserve the energy consumption in low levels. It uses the mobile multimedia sensor node, in order to augment the ability of the network for event description [57].

In this chapter the various categories of such protocols have been both presented and discussed. The appropriate use of such protocols along with multiobjective algorithms is the most effective way for alleviating the problems that obstruct the implementation of WSNs [58].

The creation and execution of efficient and dependable WSNs undeniably demand a multidisciplinary approach. Hierarchical protocols, like LEACH and TEEN, have been instrumental in advancing the field of WSNs, especially regarding the energy efficiency.

The subsequent chapter provides a comprehensive overview of the LEACH protocol and its subsequent iterations.

# CHAPTER 3:
# LEACH Protocol and its Successors

## 3.1. Introduction

In Hierarchical protocols, are structured in a hierarchical arrangement, typically consisting of clusters and CHs. The CHs aggregate data from the sensor nodes within their cluster. This involves collecting the data generated by cluster member nodes, processing it, and creating summaries or consolidated information. Data aggregation reduces the volume of data that needs to be transmitted to the BS, conserving energy and network bandwidth. Hence, they are responsible for forwarding the aggregated and processed data to the BS, which is typically located at a greater distance. This relieves individual sensor nodes from long-distance communication, which tends to consume more energy.

Hierarchical protocols can be further divided into three distinct subcategories, which are the Hierarchy-based, Zone-based, and Fuzzy logic-based protocols, depending on their data routing approach or how they partition the network area. Hierarchical-based protocols represent one of the most popular and effective subcategories of energy-efficient routing protocols in WSNs. These protocols establish a hierarchical structure within the network, typically with two levels of communication: a low level for communication between sensor nodes and CHs, and a high level for communication between CHs and the BS or sink node.

LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol is one of the most well-known and influential hierarchical protocols in the family of energy-efficient routing protocols for WSNs. LEACH have served as the foundation for various other protocols and research efforts in the field of WSNs. Other LEACH based protocols can be differentiated depending on the type of communication between the CH and the BS, as single hop and multiple hop. The choice between single hop and multiple hop communication depends on the specific characteristics of the WSN, such as its size, the required data transmission range, the available energy resources, and the desired network efficiency. Larger networks or scenarios with extended communication distances often benefit from multiple hop communication, which extends the network's reach and conserves energy. In contrast, smaller WSNs with limited data transmission requirements may find single hop communication more suitable. In large-scale WSNs, especially when dealing with long-distance communication between CHs and the BS, the choice of intermediate nodes and the communication distance between them are significant factors affecting energy consumption. This is often associated with the transmission power and the free-space path loss model, which states that energy consumption increases with distance to the power of four ($d^4$) due to the energy loss associated with signal propagation over long distances.

## 3.2. Low Energy Adaptive Clustering Hierarchy (LEACH)

LEACH protocol is a pioneering hierarchical routing protocol for WSNs [23]. The main concept of LEACH [59] is to group sensor nodes into clusters and create a mechanism for selecting CHs in a way that balances the selection process and prevents any single node from being repeatedly chosen as a CH.

LEACH consists of two phases:

a. The set-up phase and
b. The steady state phase.

During the set-up phase, the primary objectives include selecting the CH, forming clusters, and assigning a TDMA (Time Division Multiple Access) schedule to the member nodes. During the setup phase, the entity of the nodes participates in the process of selecting a CH for the current round or time period.

To determine which nodes will become CHs, each sensor node generates a random priority value that can be either 0 or 1. This priority value is usually based on a probabilistic model. If the priority of a node is less than a specified threshold, denoted as T(n), then that node assumes the role of a CH. The threshold value T(n) is determined through the following equation:

$$T(n) = \begin{cases} \dfrac{P}{1 - P \cdot \left(r \cdot mod \cdot (\frac{1}{P})\right)} & for\, n \in G \\ 0 & \end{cases}$$

where P is the percentage of the nodes to become CH, r is the current round and G is the total number of the nodes that have not been elected as CH in 1/P previous rounds. It's clear that a node that has served as a CH in round r is ineligible to be selected again in the subsequent 1/P rounds. This approach ensures a balanced method for choosing CHs and evenly distributes energy consumption. The ideal percentage of CHs has been identified as 5%. After a node is selected as a CH, it initiates the setup phase by sending an ADV message to other nodes in the network. This message typically contains information about the CH's identity, cluster formation, and the upcoming TDMA schedule. Upon receiving the ADV messages from the CHs, the remaining sensor nodes in the network decide which cluster to join. They choose the cluster associated with the CH whose ADV message is received with the highest signal strength or power level. This selection ensures that nodes connect to the nearest CH for energy efficiency. The nodes that choose to join a particular cluster send a reply message to the respective CH to confirm their membership in that cluster. The CH, now knowing the members of its cluster, creates a TDMA schedule that determines the allocated time for each member node to transmit data.

TDMA ensures that nodes within the same cluster have non-overlapping time slots for data transmission, avoiding collisions. The CH then transmits the TDMA schedule to the member nodes within its cluster. This schedule informs each node when it is allowed to transmit data or perform other tasks, creating an organized and conflict-free data transmission process. The setup phase concludes when each node within the network has received and synchronized with the TDMA schedule.

The steady state phase is crucial for the actual operation of the network, and it involves the efficient communication of data between sensor nodes, CHs, and the BS. In this phase, sensor nodes send their data to the CH to which they belong. This data transmission happens during the specific time slots allocated to each node as defined by the TDMA schedule. When a node sends data to its CH, the other nodes in the same cluster typically enter a sleep or idle mode to conserve energy.

This selective wake-up approach helps avoid congestion within the cluster and contributes to energy conservation. Implementing a TDMA schedule guarantees that nodes within the cluster transmit data in a coordinated manner, thereby minimizing the chances of data collisions and enhancing the efficiency in collecting data as a whole. After collecting data from the member nodes in its cluster, the CH aggregates and processes this data before forwarding it to the BS. The CH uses the TDMA schedule to transmit data to the BS.

As previously mentioned, LEACH achieves a balanced distribution of the CH election process among network nodes, thereby extending the network's lifespan. Furthermore, it operates without the need for a comprehensive understanding of the entire network. Additionally, the utilization of a TDMA schedule effectively prevents data collisions during transmissions. On the flip side, the protocol does not consider the remaining energy levels of nodes during the CH election process. Consequently, the probability of becoming a CH remains the same for nodes with low energy reserves as well as those with abundant energy. LEACH is also less advisable for WSNs deployed in expansive areas due to its reliance on single hop routing. Moreover, the dynamic clustering mechanism introduces additional overhead, which can offset the energy conservation benefits.

Like any protocol, LEACH has its advantages and disadvantages, as it is described in the Table 1:

| LEACH Protocol | |
|---|---|
| Pros (+) | Cons (-) |
| **Energy Efficiency**: LEACH is tailored for energy efficiency, a vital consideration in sensor networks dependent on batteries or energy-harvesting sources. It accomplishes this by implementing clustering and the rotation of CHs to evenly distribute energy consumption among sensor nodes, thereby extending the network's lifespan [60]. | **Overhead**: LEACH introduces some overhead due to the periodic clustering and CH selection processes. This can consume extra energy, especially during the initial stages [61]. |
| **Scalability:** LEACH can efficiently handle large-scale WSNs. The clustering technique alleviates the task of managing connections and routing data for every sensor node [62]. | **Unequal Cluster Sizes:** The CH selection process is randomized, which can lead to unequal cluster sizes. Some CHs may become overloaded, causing premature energy depletion [61]. |
| **Load balancing:** CHs in LEACH are rotated periodically, distributing the energy load across all nodes. This helps prevent premature energy depletion of | **Limited Security**: LEACH was primarily designed for energy efficiency, not security. It may be vulnerable to various attacks, such as eavesdropping, data tampering, or node |

| | |
|---|---|
| specific nodes, thereby extending network longevity [63]. | compromise, unless additional security mechanisms are implemented [61]. |
| **Self-organization:** LEACH is a self-organizing protocol, meaning that nodes can autonomously form clusters and elect CHs without requiring external control. This simplifies deployment and management [63]. | **Lack of QoS Support**: LEACH does not inherently support Quality of Service (QoS) guarantees, making it less suitable for applications with strict latency or reliability requirements [61]. |
| **Fault tolerance:** Since LEACH utilizes a distributed and adaptable clustering mechanism, it can adjust to node failures or alterations in network topology. This enhances the network's resilience to faults [62]. | **Inefficient for High-Density Networks:** In very high-density sensor networks, LEACH may not perform optimally, as the overhead associated with clustering and CH selection becomes more significant [61]. |
| **Low latency**: LEACH can provide relatively low latency for data transmission due to its hierarchical clustering, which reduces the number of hops required to reach the BS. | |

**Table 1**: Pros and Cons of the LEACH Protocol

### 3.3. Successors of LEACH protocol

The LEACH protocol has been widely recognized as an innovative solution in the field of WSNs, providing an energy-efficient approach for data transmission and network management. Since its inception, researchers and engineers have continuously strived to enhance and refine this protocol, giving rise to a lineage of successors and improved iterations. These successors embody a collaborative endeavor aimed at addressing the challenges and constraints encountered by the original LEACH protocol. Their central objective is to enhance energy efficiency, extend the network's lifespan, and optimize data communication. These protocols build upon the foundation laid by LEACH, incorporating novel techniques, distributed algorithms, and intelligent mechanisms to address the evolving demands of modern sensor network applications. Certain successors of the LEACH protocol employ either single-hop routing or multi-hop routing techniques, while others incorporate a hybrid approach that combines both routing methods. In single hop communication, the CH receive the transmitted by the adjacent nodes data and directly forward to the BS. Below are presented some of the most highly rated single hop LEACH successor's protocol.

An adaptation of the LEACH protocol, known as *balanced LEACH* (*LEACH-B)* has been developed. [64]. This single-hop hierarchical protocol enhances the process of cluster selection by prioritizing the residual energy of the nodes as a critical criterion. In this improved protocol, a second round of CH selection is introduced during the setup phase, considering the residual energy of the nodes on a per-round basis. To conserve energy and prolong the network's lifespan, it is imperative that the protocol ensures a balanced and uniform distribution of clusters. To achieve this objective, the protocol seeks to control the number of CHs, aiming for an optimal quantity of CHs within the network. When choosing CHs, the process considers both the target percentage of CHs and the remaining energy of the nodes. In practice, a portion of the CHs is selected randomly, taking into account their available residual energy. If the count of randomly chosen Cluster Heads (CHs) is below the result of the multiplication of 'n' (the total number of nodes) by 'p' (the desired percentage of CHs), then various regular nodes are assigned the role of CHs. Conversely, if this count surpasses the product of 'n' and 'p', CHs with low energy levels are omitted to maintain the intended number of CHs, which is equal to 'n' times 'p'. To accomplish this, all CHs are organized in a descending order according to their remaining energy levels. Those CHs that fall below 'n' times 'p' are transformed into regular nodes.

LEACH-B enhances the distribution of energy load among clusters, resulting in reduced energy consumption for sensor nodes. It's important to acknowledge that this protocol does have some limitations, such as increased message overhead, scalability challenges, and increased complexity.

Another well-known hierarchical protocol that supports single-hop communication and significantly improves energy efficiency while extending the lifetime of WSNs is the Modified LEACH, often referred to as Mod-LEACH. [65] This protocol introduces the concept of an energy threshold for the creation of clusters and the selection of CHs. The energy threshold represents a minimum value used in the process of CH creation and selection for the upcoming round. If the current cluster possesses more energy than this threshold, it will retain its status as a CH for the next round. If the current cluster's energy falls below this threshold, it will be replaced following the principles of the original LEACH algorithm. Furthermore, Mod-LEACH incorporates two distinct power levels for signal amplification. An Intra-Cluster transmission which refers to communication within a cluster, primarily involving the exchange of data among the nodes within the same cluster and an Inter – Cluster transmission, when CHs need to relay data or information between clusters. It's important to note that the energy requirements for amplification in inter-cluster communication and intra-cluster communication are not the same. The minimum energy needed for amplifying signals during communication between CHs and the BS differs from the amplification energy needed for communication within individual clusters. This differentiation helps optimize energy consumption and enhances the overall efficiency of Mod-LEACH in WSNs.

Another member of the single-hop routing protocol family is the Centralized LEACH, often referred to as LEACH-C, as described in [66]. Unlike some other decentralized protocols, LEACH-C employs a central control algorithm for the creation of clusters during both the setup and steady-state phases, similar to the fundamental LEACH algorithm. In this centralized approach all critical decisions, including the selection of CHs, the formation of clusters, and the distribution of information throughout the network, are orchestrated and executed by the BS. By centralizing control and decision-making, LEACH-C offers a different approach to network management and optimization, with the BS playing a pivotal role in network coordination and management.

Since one of the major disadvantages of the WSN is the power supply, many researches have made in order to supply the nodes with extra sources of energy. A protocol that introduces this idea is the *solar aware LEACH (sLEACH)* [67]. In this single hop routing protocol, solar power is added into some nodes as an extra source of energy and these nodes are the CHs. The BS chooses as CHs all these nodes having additional powered by solar. If the number of nodes that have solar energy increases, then the network's lifespan will also extend .Security stands as a substantial concern in the domain of WSNs. In response to this concern, researchers have introduced the *security based LEACH (SLEACH)* [68]. SLEACH is a single-hop routing protocol that distinguishes itself as the pioneer in addressing security issues within WSNs. It accomplishes this through the utilization of lightweight cryptographic techniques, marking a pivotal step in enhancing the security of WSNs.

Another notable single-hop routing protocol in the realm of WSNs is the *Quadrant Cluster-based LEACH* (Q-LEACH) [69]. Q-LEACH draws from both the characteristics of Q-DIR (Quadrant-Based Directed Diffusion and Restricted Flooding) routing techniques and the LEACH protocol. Q-DIR routing, at its core, is a consolidation of location-based routing and controlled flooding strategies. Within the Q-LEACH protocol, the FOI gets segmented into four quadrants and clusters are created within each of these quadrants. This approach leverages the advantages of both location-based routing and the LEACH hierarchical structure, offering an innovative solution for data transmission and management in WSNs.

The *Time Based LEACH (TB-LEACH)* [70] is another single hop communication routing protocol and it is based on time in order to overcome LEACH's problem. It uses an interval time based on a threshold where the CH is selected. The CHs are chosen among the nodes with the briefest time intervals. In *Advanced LEACH (A-LEACH)* [71] a novel technique for CH selection in each round is introduced. The selection of CHs in this protocol is influenced by two crucial factors: the current state probability (CSp) and the general probability (Gp). Consequently, the threshold value required to become a CH is determined by a combination of these two terms in every round. This approach offers a more refined and adaptive method for CH selection, enhancing the protocol's efficiency and adaptability in Wireless Sensor Networks.

A well-known single hop protocol is the *Threshold LEACH (T-LEACH*) [72] in which the selection of the CH doesn't depend only on the node's residual energy, but also takes under consideration threshold energy. As long as the remaining energy of a CH is higher than the threshold energy this node remains CH. Only when that threshold is exceeded, a new round will start again.

A refinement to the LEACH protocol has been recommended, incorporating a fuzzy logic approach, known as *the fuzzy logic based LEACH (FL-LEACH)* [73]. FL-LEACH leverages the Mamdani inference method, which is a widely adopted fuzzy logic technique. Notably, this method has been previously used in controlling a steam engine and boiler combination. [74] The primary advantage of FL-LEACH is its capacity to compute the ideal number of CHs before deploying the network. By utilizing fuzzy logic, FL-LEACH offers a refined and data-driven approach to CH selection, leading to improved network efficiency and performance.

In *improved LEACH (I-LEACH)* [75], factors that affect the performance of the network such as network lifetime, energy efficiency etc., are taking under consideration in order to improve the condition of the WSN. More particular, in order a node to be selected as CH, not only the remaining energy acts as criterion but also the number of the node next to it and the position of the node from the BS.

In the multi hop communication there is an intermediate step between BS and CH. The follow protocols belong to multi hop routing protocol family and explore the underlying principles, challenges, and strategies employed to establish reliable, energy-efficient, and robust communication paths. By investigating this intricate interplay between sensor nodes, CHs, and the BS, is aimed to shed light on the pivotal role played by multi-hop communication in enhancing the effectiveness and longevity of WSNs.

The *Multihop Routing LEACH (MR - LEACH)* protocol as described in [76] aims to optimize the network's lifetime by employing multiple levels of clusters. In this approach, CHs at each level collaborate with adjacent levels to facilitate data transmission from nodes to the BS. Regular nodes join CHs based on their Received Signal Strength Indication (RSSI). The BS selects upper-level CHs to act as super CHs for lower-level CHs. Consequently, MR-LEACH adopts a multi-hop routing strategy from CHs to the BS, diverging from the direct single-hop transmission used in the LEACH protocol. MR-LEACH is divided into two phases, similar to LEACH: the setup phase and the steady-state phase. The setup phase aligns with LEACH's setup phase. However, during the steady-state phase, CHs located further from the BS serve as intermediate nodes to relay data to the BS, while CHs closer to the BS directly transmit data to the BS. Compared to the basic LEACH, MR-LEACH boasts superior energy efficiency and scalability. However, the introduction of multi-path transmission through relay nodes does increase the network's complexity and overhead. Nonetheless, this approach effectively balances energy consumption and extends the network's lifetime.

Another protocol of this family is the *Two Level LEACH (TL-LEACH)* [77]. Similar to LEACH protocol, it operates in a clustered hierarchy. In addition to the primary cluster, it creates secondary clusters within each primary cluster. So, each primary cluster consists of multiple secondary clusters. Secondary clusters are formed by dividing the primary cluster’s area or network region further to smaller subsets. CH selection occurs at both the primary and secondary cluster levels. In the initial phase, primary Cluster Heads (CHs) are designated in a way that mirrors the original LEACH protocol, utilizing a probabilistic approach that relies on a rotating schedule. Secondary CHs are then selected from among the nodes within each primary cluster, ensuring balanced energy consumption within secondary clusters. Primary CHs aggregate data from secondary CHs and their respective nodes in the primary cluster. Secondary CHs aggregate data from the nodes that participate in these CHs within the secondary cluster. Aggregated data is then sent to the BS through multi-hop communication, reducing the energy expenditure of individual nodes. By introducing secondary clusters, the protocol reduces the distance over which data needs to be transmitted, saving energy.

*Energy-LEACH (E-LEACH),* as outlined in [78] has made notable improvements to CH selection and data transmission between CHs and the BS in comparison to the LEACH protocol. One of the key innovations in E-LEACH is its dynamic CH selection process. Unlike LEACH, where CHs are randomly selected in each round, E-LEACH introduces a mechanism that takes into account the remaining energy levels of sensor nodes. Nodes with higher energy levels are granted a higher probability of being selected as CHs, contributing to a more balanced energy distribution across the network. E-LEACH also incorporates a CH rotation mechanism, ensuring that nodes take turns serving as CHs over multiple rounds. This rotation strategy promotes an even distribution of energy consumption among sensor nodes, preventing some nodes from depleting their energy rapidly. CHs in E-LEACH have the responsibility of collecting data from their associated member nodes, processing and aggregating the data, and subsequently transmitting it to the BS. Through its dynamic CH selection based on energy levels and the implementation of rotation strategies, E-LEACH appears to have better performance in terms of energy consumption and efficiency compared to the original LEACH protocol. This leads to a network life.

In *Enhanced LEACH (E-LEACH)* [79] , the main idea is the optimal choice of the number of CHs while varying the round time in every round. It often incorporates dynamic CH selection mechanisms that consider factors such as node energy levels, distance to the BS, and network topology. This helps in optimizing the choice of CHs for each round of data collection. Enhanced LEACH may include energy-efficient routing algorithms that determine the optimal paths for data transmission within the network.

*LEACH - mobile (LEACH – M)* [80], has been introduced in order to support mobility to the nodes. The set-up phase is the same as it is in LEACH protocol but the steady state – phase different is that one CH assumes that if one node doesn't responses in the data request messages, the nodes has moved to another cluster.

An extension of this protocol is the *LEACH Mobile Extended (LEACH –ME)* as described in [81]. In LEACH-ME, the criteria for designating a node as a CH are primarily based on the mobility of the node and the attenuation model. The protocol favors nodes with lower mobility and reduced attenuation power, making them more likely to be chosen as CHs. This unique CH selection strategy accounts for the specific characteristics of nodes and their movement patterns, enhancing the efficiency of the network.

Another protocol using multiple hop communication is the *LEACH based on Density* of node distribution *(LEACH-D*) [82]. It designed to address the issue of non-uniform node distribution WSNs. In traditional LEACH, CHs are selected randomly, which may lead to some clusters having more CHs than others in densely populated areas and, consequently, uneven energy consumption. LEACH-D takes into account the density of nodes in different areas to improve the clustering and energy efficiency of the network. LEACH-D employs data regarding the node density across various network regions to establish clusters. In areas with a higher node density, the probability of a node becoming a CH is reduced, while in sparser areas, nodes are more likely to become CHs. This density-aware approach aims to balance the number of CHs across the network, ensuring that densely populated areas do not become CH hotspots. By distributing CHs based on node density, LEACH-D helps in reducing energy consumption in densely populated areas. CHs in dense regions are less frequent, meaning nodes in those areas do not deplete their energy as quickly as they might in a traditional LEACH-based network.

*LEACH One Round (LEACH -1R)* [83] is a simplification of the original LEACH protocol. In the standard LEACH protocol, CHs are rotated on a probabilistic basis over multiple rounds to distribute the energy consumption evenly across nodes. In contrast, LEACH-1R simplifies this process by having nodes select CHs for only one round, and then the clusters are reformed in the next round. In LEACH-1R, nodes in the network elect CHs for a single round only. This approach differs from the original LEACH protocol, where CHs are elected for multiple rounds in a probabilistic manner. LEACH-1R simplifies the clustering process by eliminating the need for nodes to perform probabilistic calculations to decide whether they should become CHs. Instead, nodes take on the role of CH for a single round in a more deterministic manner. The simplification in LEACH-1R reduces the communication overhead associated with CH selection and cluster formation. This can result in energy conservation throughout the network.

*Energy Efficient -LEACH (EE-LEACH)* as discussed in [84] has as primary objective to ensure equitable energy consumption among sensor nodes. It achieves this by dynamically selecting CHs based on their remaining energy levels. Nodes with greater energy reserves have a higher likelihood of being chosen as CHs, resulting in a more equitable distribution of the energy load throughout the network. EE-LEACH also incorporates advanced techniques for efficient data aggregation and fusion at the CH level. This approach significantly reduces the volume of data transmitted across the network, leading to lower energy consumption and enhancing network scalability. Also, EE-LEACH can implement energy-aware routing algorithms that optimize the selection of energy-efficient paths for data transmission within the network. This further minimizes energy wastage during data forwarding, making EE-LEACH a promising solution for great energy efficiency in WSNs.

The *Simulated Annealing and Genetic Algorithms LEACH (SAGA-LEACH*) as detailed in [85], introduces a novel approach to selecting nodes as CHs. In contrast to the random selection process employed by the traditional LEACH, SAGA-LEACH utilizes a combination of simulated annealing and genetic algorithms to determine the CHs. This innovative approach leverages optimization techniques from these algorithms to make informed decisions about CH selection, potentially leading to more efficient and effective CH assignments in Wireless Sensor Networks.

The *Multi-hop and Single Hop Routing LEACH (MS-LEACH)* described *in* [86] introduces a hybrid approach that allows for both single-hop and multi-hop communication within clusters based on a critical value related to cluster size. During the setup phase, MS-LEACH adheres to the same procedure as the original LEACH protocol. However, in the steady-state phase, the decision to use single-hop or multi-hop communication between CHs and member nodes within the cluster is established according to a critical threshold. The critical threshold is linked to the cluster size and is calculated by the CH when it possesses information about the total number of nodes and their positions within the cluster.MS-LEACH offers flexibility in choosing the most suitable communication mode based on the specific cluster characteristics, optimizing data transmission and energy consumption within the network.

The *Data Aggregation based Optimal- LEACH (DAO –LEACH)* protocol detailed in [87] has been devised to reduce energy consumption in sensor nodes and optimize resource utilization. This protocol comprises four key stages: node deployment where nodes are deployed in the network according to a Gaussian normal distribution formula, aiming to achieve better network coverage, cluster formation based on the optimal number of CHs selected , optimal numbers of CH selection and node aggregation via data ensemble. The last stage is achieved through the selection of an aggregator node, referred to as a macro node (M). This macro node, comprising more than one regular node, plays a pivotal role in the data aggregation process. Path definition and the aggregation operation by the macro node are performed through conditional probability. Following the completion of these stages, an energy-efficient path is established to transmit aggregated data from source nodes to the BS. This multi-stage approach optimizes data aggregation, reduces energy consumption, and enhances the overall efficiency of the network.

In Table 2, a comparison among protocols that belong in the single hop family protocols based on performance parameters.

| Leach Successors | Routing Technique | Overhead | Scalability | Energy Efficiency | Complexity | Delay |
|---|---|---|---|---|---|---|
| LEACH-B | Single Hop | Elevated | Limited | Elevated | Elevated | Elevated |
| LEACH-C | | Elevated | Limited | Elevated | Adequate | Small |
| LEACH-CE | | Very high | Limited | Very high | Adequate | Small |
| I-LEACH | | Very high | Very high | Very high | Elevated | Small |
| U-LEACH | | Elevated | Limited | Elevated | Elevated | Small |
| V-LEACH | | Very high | Limited | Very high | Very high | Elevated |
| T-LEACH | | Elevated | Elevated | Elevated | Elevated | Small |
| sLEACH | | Very high | Adequate | Very high | Elevated | Small |

**Table 2:** Comparison of single hop LEACH's successors.

In Table 3, a comparison among protocols that belong in the multiple hop family protocols based on performance parameters.

| Leach Successors | Routing Technique | Overhead | Scalability | Energy Efficiency | Complexity | Delay |
|---|---|---|---|---|---|---|
| O-LEACH | Multiple Hop | Elevated | Elevated | Elevated | Elevated | Elevated |
| DL-LEACH | | Elevated | Elevated | Elevated | Limited | Adequate |
| MR-LEACH | | Elevated | Elevated | Elevated | Elevated | Elevated |
| Cell-LEACH | | Adequate | Very high | Adequate | Very high | Adequate |
| LEACH-1R | | Elevated | Limited | Elevated | Elevated | Small |
| WLEACH | | Very high | Elevated | Very high | Limited | Small |
| LEACH-D | | Very high | Very high | Very high | Very high | Small |
| LEACH-L | | Elevated | High | Elevated | Elevated | Elevated |
| TL-LEACH | | Elevated | Limited | Elevated | Limited | Small |

**Table 3:** Comparison of multiple hop LEACH's successors.

# CHAPTER 4: Energy Conservation Techniques in WSNs

## 4.1. Introduction

As the reliance on WSNs continues to grow, the need for sustainable and efficient energy management strategies becomes increasingly evident. These networks play pivotal roles in environmental monitoring, precision agriculture, industrial automation, and countless other applications. Whether tracking wildlife in the wilderness, monitoring vital signs in healthcare, or optimizing manufacturing processes, the fundamental challenge remains the same: how can be maximized the lifespan of these resource-constrained nodes while ensuring they fulfill their crucial roles. The answer lies in a myriad of innovative techniques and strategies, each designed to eke out every precious joule of energy from these miniature powerhouses. From hardware optimizations to intelligent data handling, and from adaptive sampling to duty cycling, the realm of energy conservation in WSNs is a tapestry woven with technical ingenuity.

In this chapter, the intricacies of these energy-saving methodologies and their profound impact on the resilience and longevity of these networks are explored.

## 4.2. Low – Power Listening – (LPL)

Low-Power Listening (LPL) [88] is a power-saving technique used in WSNs to reduce energy consumption during idle periods while maintaining the ability to receive incoming messages. LPL is particularly crucial in WSNs because sensor nodes are often use battery as energy source and must function for extended durations without frequent battery replacements.

In WSNs, sensor nodes frequently alternate between active (listening) and sleep (low-power) modes. During the active mode, nodes are ready to receive incoming messages, while during the sleep mode; they consume minimal power or even power down entirely to conserve energy. Instead of staying continuously active, which would drain the battery quickly, LPL relies on periodic wake-up intervals. Nodes intermittently awaken to search for incoming messages and subsequently revert to a sleep mode in the absence of any messages. The length and timing of these wake-up intervals can be adjusted based on the application requirements. During the active mode, nodes open a listening window during which they are ready to receive incoming messages. This window is usually shorter than the active period itself to conserve energy further. Messages can be sent by neighboring nodes during this listening window. To ensure that nodes wake up and enter their active mode at roughly the same time, synchronization protocols may be employed. These protocols help avoid collisions and improve the overall efficiency of communication. Such protocols are Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol with Clear Channel Assessment (CCA) to be sure the media is free.

In Table 4, some of the advantages and disadvantages of this technique are presented.

| LPL Technique | |
|---|---|
| **Pros (+)** | **Cons (-)** |
| **Energy Efficiency**: LPL significantly reduces energy consumption during idle periods, extending the battery life of sensor nodes. [89] | **Latency**: LPL typically introduces additional latency in communication. Since devices spend most of their time in low-power modes and wake up periodically to listen for incoming data, there can be delays in transmitting and receiving information. This latency can be problematic for applications that require real-time or low-latency communication. [90] |
| **Reduced Interference:** By synchronizing listening windows, LPL reduces the likelihood of packet collisions and interference, improving the overall reliability of communication [91] | **Limited Data Throughput**: LPL is more suited for low-data-rate applications. The intermittent listening schedule and low-power states can limit the overall data throughput of a network. In scenarios where high data transfer rates are required, LPL may not be the most suitable communication technique. [90] |
| **Scalability:** LPL can be applied to large-scale WSNs, allowing for efficient communication in networks with a large number of nodes. [92] | **Trade-Offs with Duty Cycling**: LPL is just one form of duty cycling, and there are trades-offs between different duty cycling schemes. Depending on the specific requirements of an application, other duty cycling methods may be more suitable, and LPL might not be the optimal choice [90]. |
| **Real-Time Responsiveness:** LPL allows sensor nodes to remain responsive to incoming messages while conserving energy during idle times, making it suitable for applications that require real-time data collection [93]. | **Interference Susceptibility**: LPL relies on specific time slots or conditions for communication. In environments with high interference or unpredictable radio conditions, devices may struggle to establish reliable communication due to increased contention and collisions [90]. |

**Table 4**: Advantages and Disadvantages of LPL Technique

In summary, while Low-Power Listening offers energy-saving benefits and extends battery life in wireless sensor networks, it comes with trade-offs such as increased latency, complexity, and limitations on data throughput. When implementing LPL, it's crucial to carefully consider the specific requirements and constraints of the application to determine whether the advantages outweigh the disadvantages.

### 4.3. Low – Power Probing – (LPP)

Low-Power Probing (LPP) is a technique used in wireless communication systems, particularly in WSNs to reduce power consumption during the discovery and establishment of network connections. LPP is designed to minimize energy consumption when devices are searching for and establishing communication links, which is crucial for battery-powered devices with limited energy resources [94].

In wireless communication, devices often need to scan for nearby networks or available peers before initiating a connection. Conventional scanning techniques entail the active transmission of probe requests and the listening for responses, a process that can result in notable energy consumption. LPP, on the other hand, employs energy-efficient scanning techniques. Instead of actively transmitting probe requests, LPP devices primarily rely on passive listening. They listen for incoming signals or beacon frames from nearby devices or access points without actively sending any signals themselves. This reduces the energy consumption associated with transmitting radio signals. LPP devices periodically wake up from low-power sleep modes to scan for beacon frames or signals from potential peers or access points. The wake-up intervals are typically longer than traditional active scanning periods to reduce the time spent in active mode and, consequently, the energy consumption.

In Table 5, some of the advantages and disadvantages of this technique are presented.

| LPP Technique | |
|---|---|
| **Pros (+)** | **Cons (-)** |
| **Energy Efficiency:** LPP significantly reduces the energy consumption associated with network discovery and establishment, making it well-suited for battery-powered devices with limited energy resources [94]. | **Longer Connection Setup Times**: LPP's reliance on passive listening and infrequent active scanning can lead to longer connection setup times compared to traditional active scanning methods. In cases where quick network access is crucial, this delay may be a disadvantage [95]. |
| **Prolonged Battery Life**: By minimizing the time spent in active mode and transmitting signals, LPP helps extend the battery life of wireless devices [94]. | **Limited Discovery Range**: Passive listening in LPP may limit the range at which devices can discover and establish connections with other devices or networks. This limitation can be a drawback in scenarios where long-range communication is required [95]. |
| **Reduced Interference:** Passive listening and selective active scanning reduce the likelihood of collisions and interference, improving the overall reliability of network discovery and connection establishment. [94] | **Trade-Offs with Timeliness**: While LPP conserves energy; it does so at the cost of timeliness. In applications where rapid network discovery and connection establishment are critical, the energy savings achieved by LPP may not outweigh the time delay [95]. |

**Table 5**: Advantages and Disadvantages of LPL Technique

Low-Power Probing helps strike a balance between energy efficiency and the need to discover and connect to nearby networks or devices in a power-efficient manner.

While it offers significant energy savings, it may not be the best choice in situations where rapid network discovery, fine-grained control, or long-range communications are paramount.

## 4.4. Sleep Scheduling Technique

Sleep scheduling in WSNs is a crucial technique for conserving energy in sensor nodes while maintaining the network's functionality. Sleep scheduling involves periodically turning nodes on and off to minimize energy consumption during idle periods. In the sleep periods, the radios are completely powered down, and during active periods, they are reactivated to transmit and receive messages [96]. Duty cycling is a fundamental sleep scheduling technique in WSNs. Nodes alternate between active and sleep modes, with defined time intervals for each. During the active period, nodes perform sensing, data processing, and communication, while during the sleep period, they switch to low-power mode. Adaptive sleep scheduling adjusts the duty cycle dynamically based on network conditions, traffic patterns, and energy levels. Nodes may reduce their active periods during periods of low activity to save energy. In large-scale WSNs, hierarchical sleep scheduling organizes nodes into clusters with a CH responsible for managing communication. CHs stay awake more often to relay data, while other nodes in the cluster follow a more aggressive duty cycle. Nodes wake up in response to detected events or triggers, such as the sensing of a specific event or when a predefined threshold is met. This technique minimizes unnecessary wake-ups and is suitable for applications where event detection is critical.

An algorithm that is used for this technique is called Listen – Before – Talk (LBT). [97] Before a device attempts to transmit data over a wireless channel, it first listens to the channel to check for any ongoing transmissions by other devices. This listening is crucial to avoid interference and collisions. The device performs a Clear Channel Assessment (CCA) to determine if the channel is "clear," meaning there are no ongoing transmissions or strong interference. This typically involves checking the received signal strength (RSSI) and carrier sense information. If the channel is determined to be busy (i.e., other devices are currently transmitting), the device enters a back off state. During this state, the device waits for a random period before reattempting to sense the channel. This randomization helps reduce the likelihood of multiple devices retrying simultaneously and colliding again. Once the back off period expires and the channel is clear, the device can attempt to transmit its data. If the channel remains busy after the back off period, the device may continue to extend the back off time and retry until it successfully accesses the channel.

In Table 6 some of the advantages and disadvantages of this technique are presented.

| Sleep Scheduling Technique | |
|---|---|
| Pros (+) | Cons (-) |
| **Energy Efficiency**: The primary advantage of sleep scheduling is its ability to significantly reduce energy consumption in sensor nodes. By periodically entering low-power sleep modes, nodes conserve energy during idle periods, thus prolonging their battery life. [98] | **Increased Latency**: Sleep scheduling can introduce latency in data transmission because nodes need to wake up from sleep mode before participating in communication. This latency may be unacceptable for time-sensitive applications. [98] |
| **Extended Network Lifetime**: Sleep scheduling contributes to a longer network lifetime. By conserving energy, nodes can continue to operate for extended periods without the need for frequent battery replacements or recharging. [98] | **Complexity**: Implementing sleep scheduling can be complex, especially in large-scale networks with dynamic conditions. Designing effective scheduling algorithms and ensuring synchronization among nodes can be challenging. [98] |
| **Optimized Network Performance**: Adaptive sleep scheduling algorithms can dynamically adjust the duty cycle based on network conditions, traffic patterns, and energy levels. This optimization ensures that nodes are awake when needed and asleep when not, leading to improved network performance. [98] | **Loss of Real-Time Data**: In some sleep scheduling schemes, nodes may sleep for extended periods, potentially missing real-time data or events. This can be a significant drawback for applications that require continuous monitoring. [98] |
| **Event-Driven Operation**: Sleep scheduling allows nodes to wake up in response to specific events or triggers, which is particularly useful for applications where real-time event detection is essential. This minimizes unnecessary energy consumption. [98] | **Impact on Routing**: Sleep scheduling may affect routing decisions in WSNs, as nodes' availability and connectivity change dynamically. This can complicate the routing protocol design. [98] |

**Table 6**: Advantages and Disadvantages of Sleep Scheduling Technique

## 4.5. Energy Efficient Clustering & Scheduling Algorithm

Energy-efficient clustering and scheduling algorithms (ECSA) play a vital role within WSNs as they are crucial for prolonging the network's lifespan by preserving the energy of sensor nodes. These algorithms aim to optimize the way sensor nodes are organized into clusters and how they schedule their operations to minimize energy consumption while meeting application requirements. [99] These algorithms are the fundamental algorithms used by the most common protocols such as LEACH etc., because they allow the cluster formation and the CH selection as action for energy conservation and network lifetime prolonging.

## 4.6. Energy Efficient Clustering and Scheme

The Energy Efficient Clustering and Scheme (EECS) is a hierarchical clustering approach developed to improve the endurance of WSNs by optimizing energy utilization. [100]

EECS achieves this goal through the following key features. A dynamic CH selection mechanism based on the energy levels of nodes. CHs are more likely to be chosen from nodes with higher remaining energy. This strategy helps balance energy consumption throughout the network. On the other hand, EECS utilizes multi-hop communication to reduce transmission distances, conserving energy and improving efficiency. Hence, EECS utilizes multi-hop communication to reduce transmission distances, conserving energy and improving efficiency. The method employed by EECS produces a near-uniform distribution of CHs, preventing concentration and ensuring equitable network management. EECS introduces a novel approach in the cluster formation phase to balance the load among CHs. Simulation results have demonstrated that EECS significantly prolongs the network lifetime, extending it up to 135% compared to the traditional LEACH protocol. This makes EECS a promising solution for energy-efficient and long-lasting WSNs.

## 4.7. Localized Energy Consumption Technique

Localized energy consumption (LEO) techniques in WSNs focus on minimizing energy consumption within a localized area or region of the network. These techniques are particularly important in scenarios where certain parts of the network may need to conserve energy due to limited power sources or to ensure the network's longevity.

The Localized Energy Conservation Algorithm (LECA) is an exemplar of techniques aimed at reducing energy consumption in networks while preserving performance levels. In LECA, a small subset of nodes, referred to as coordinators, is chosen to participate in the routing process, while the remaining nodes are placed in a low-power state to conserve energy. The distinguishing feature of LECA is that the number of coordinators selected is lower than in existing methods. This unique approach allows the network to maintain high performance levels, even with a sparse set of coordinators. This minimizes energy consumption, resulting in an efficient and energy-conserving network. [101]

In the subsequent chapter, a survey of network simulators is presented, offering insights into tools and methodologies used for simulating and analyzing various aspects of network performance and behavior.

# CHAPTER 5:
# Network Simulators Survey

## 5.1. Introduction

Simulation is a computational technique used to model and analyze the behavior of a network on a computer. It involves performing mathematical calculations and utilizing various metrics to understand and predict the performance, characteristics, and dynamics of the network. By simulating network scenarios, researchers and engineers can gain insights into how a network is likely to function under different conditions, helping them make informed decisions and optimizations. [102] As the demand for efficient and scalable communication systems continues to rise, the role of network simulators in WSN has become increasingly vital.

As we have seen until now, WSN have an extensive scope of application. However, developing and testing these networks in the real world can be prohibitively expensive, time-consuming, and complex. This is where network simulators shine. They provide a virtual playground where researchers and engineers can design, assess, and refine their WSNs without the constraints of the physical environment. Network simulators offer a safe and cost-effective means to explore various scenarios, protocols, and algorithms, allowing for rapid prototyping and informed decision-making.

In the vast landscape of modern technology, Open Source Software (OSS) stands as a beacon of innovation, collaboration, and freedom. This prologue marks the beginning of a journey into the heart of OSS, a realm where lines of code intertwine with the principles of open sharing and collective creativity.

Open Source Software, often referred to as "OSS," represents a paradigm shift in the way we develop, distribute, and use software. At its core, OSS embodies the idea that software should be a shared resource, accessible to all, and constantly evolving through a global community of passionate contributors. It challenges the conventional wisdom of proprietary software and offers an alternative path, one where collaboration reigns supreme. [103]. Some of these simulators are presented in what follows in this Chapter.

## 5.2. Network Simulator v2 / v3 (NS-2 / NS-3)

Network Simulator, often abbreviated as NS, encompasses two widely used open-source simulation tools: NS-2 (Network Simulator version 2) and NS-3 (Network Simulator version 3). These simulators are essential tools in the field of computer networking and are utilized for research, development, and education purposes. Both are open source and free of charge and can simulate TCP, Multicast Protocols, and Wireless and Wired networks. NS2 was developed in 1995 at the University of California, Berkeley. It is written in C++

and TCL (Tool Command Language). TCL is used for configuration and scripting, while C++ is employed for core simulation components. NS-2 is known for its extensive library of network models and protocols. It allows users to create custom network topologies, define protocols, and simulate various network scenarios. NS-2 has some limitations, such as its complex configuration process, a steep learning curve, and the fact that it uses TCL, which some users find less intuitive compared to other scripting languages. A significant drawback of NS-2 is that it cannot quantify the energy consumption of the hardware, software, and components within WSN nodes. In Figure 6 the GUI – Graphical User Interface of NS-2 is illustrated.

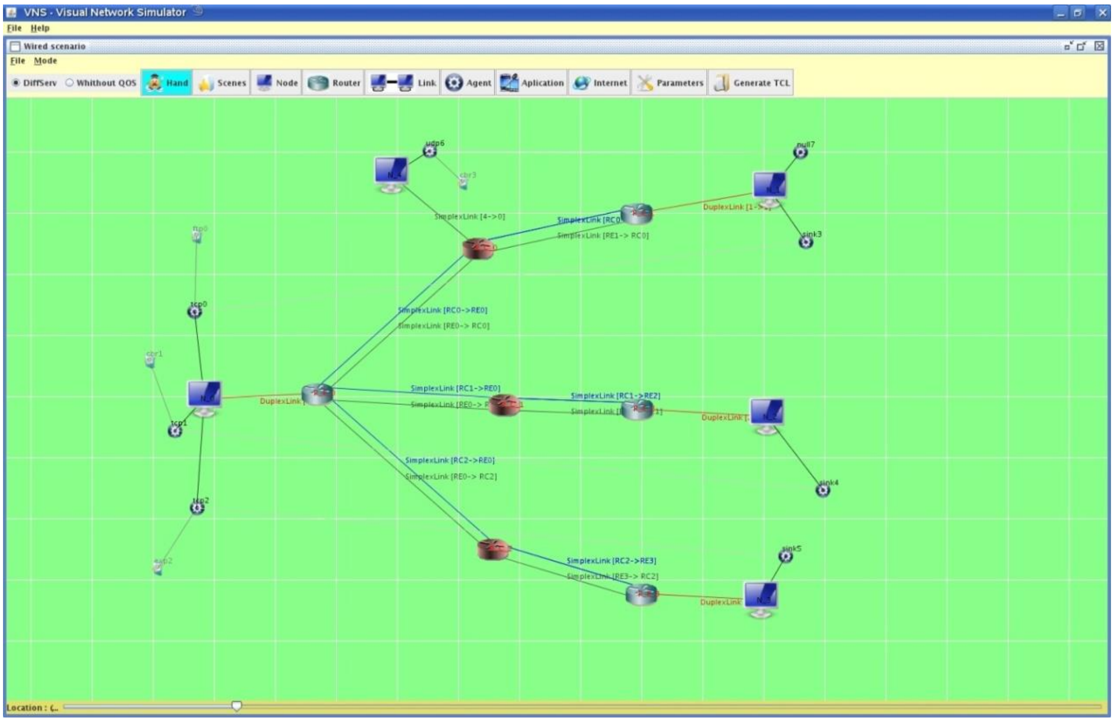


**Figure 6**: Topology representation in NS-2

On the other hand, NS-3 is also a network simulator that was deployed in 2006 and is primarily implemented in C++, which makes it more efficient in terms of simulation runtime and provides flexibility for integrating with other C/C++ libraries, with Python scripts [104].

NS-3 offers a modern and modular architecture that allows users to easily add or modify network components. It provides support for wireless, Internet, and various other network technologies. NS-3 is designed to be more realistic and accurate in its simulations.

A key advantage of this protocol is that contains virtualization and updated models and it is often used for performing large scale network simulation.
Figure 7 shows the GUI of NS-3 platform:

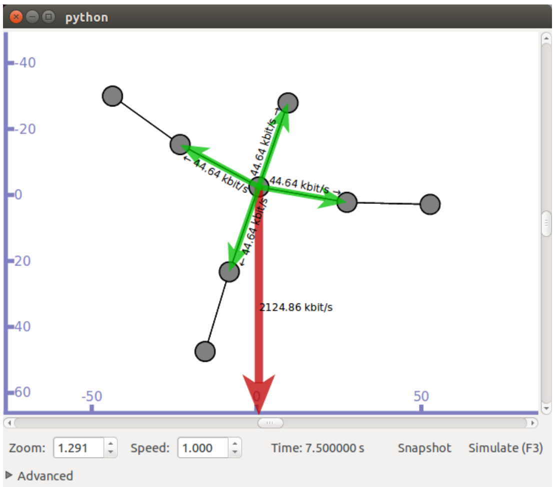


**Figure 7**: Topology representation in NS-3

## 5.3. Objective Modular Network Testbed in C++ (OMNET++)

OMNeT++ (Objective Modular Network Testbed in C++) is a widely used open-source discrete event simulation framework for modeling and simulating complex communication networks, protocols, and distributed systems. OMNeT++ is a versatile and extensible simulation library and framework that is primarily used for constructing network simulators. This C++-based tool provides a modular and component-based approach to creating simulations and offers a range of features to support this endeavor. OMNeT++ is distributed under the Academic Public License. [105]

OMNeT++ provides a graphical runtime environment, making it easier to visualize and interact with simulations. Extensions are available for real-time simulation, allowing researchers and engineers to study the real-time behavior of network systems.

OMNeT++ supports network emulation, which is useful for mimicking real-world network conditions and behaviors in a controlled environment. It offers features for integrating simulation data with databases, facilitating data analysis and storage.

Overall, OMNeT++ is a valuable tool for researchers, developers, and educators working on network-related simulations and studies. Its modular and extensible nature, along with various extensions and features, makes it a powerful resource for network simulation and analysis.

Figure 8 shows the graphical representation of a network and the animation for packet transmission.

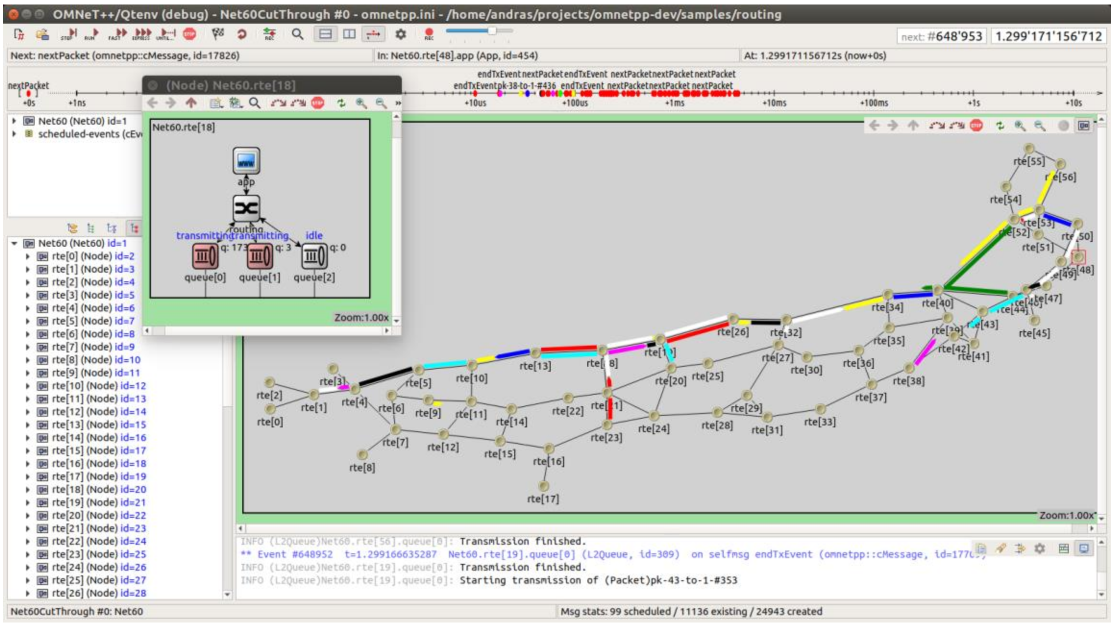


**Figure 8**: Animated packet transmissions in a network

## 5.4. Optimized Network Engineering Tools (OPNET)

OPNET Network simulator is a tool to simulate the behavior and performance of any type of network, including wired and wireless networks, ad-hoc networks, cloud computing environments, and more. The main difference OPNET Network Simulator comparing to other simulators lies in its power and versatility. OPNET offered a graphical modeling environment where users could design and configure network topologies, define network elements, and specify communication protocols and behaviors. This made it accessible to users with varying levels of technical expertise.

IT Guru is a network simulation tool that offers a collection of pre-built models for various network protocols and devices. However, it's important to note that in IT Guru, the set of protocols and devices is typically fixed and predefined. Users usually cannot create entirely new protocols or modify the behavior of existing ones within the tool. Instead, they work with the provided set of models to simulate, analyze, and experiment with network scenarios based on the available protocols and devices. This makes IT Guru a useful resource for network simulations within the constraints of the provided models but may not be as flexible as tools that allow users to create custom protocols and extensively modify existing ones.

OPNET allowed for real-time and discrete event simulation, enabling users to assess how networks would behave under various conditions, including changes in traffic load, network failures, and congestion scenarios.

The big advantage of OPNET is that can support the modeling of diverse scenarios, such as capacity planning, network optimization, and quality of service (QoS) assessment. This made it applicable in industries like telecommunications, data centers, and cloud computing.

It is based on C++ and proposed in 1986 by MIT [106]. Figure 9, shows the GUI of OPNET.

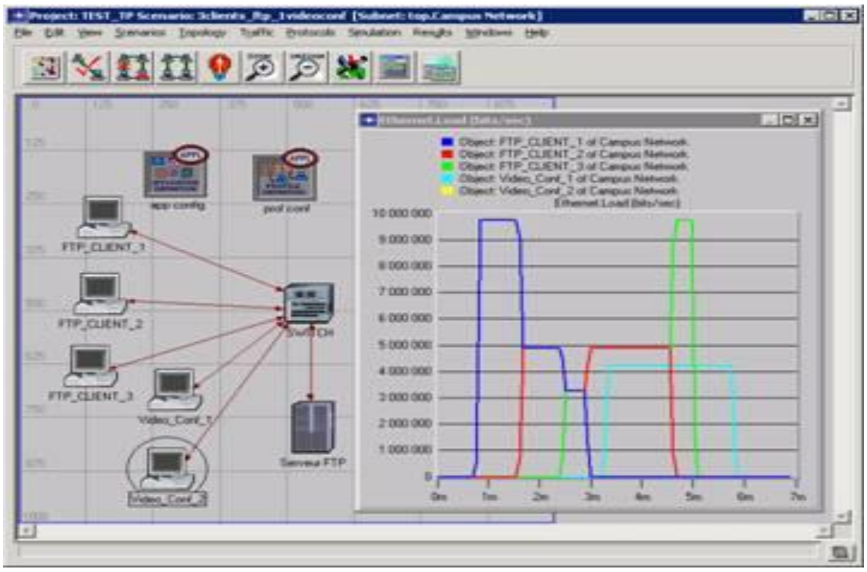


**Figure 9**: OPNET GUI

## 5.5. MAThematical LABoratory (MATLAB)

In 1984, MathWorks introduced MATLAB, which blends a desktop environment optimized for repetitive analysis and design procedures with a programming language that enables direct manipulation of matrix and array mathematics. It finds extensive applications in a multitude of domains, encompassing mathematics, engineering, science, and finance. MATLAB provides a powerful set of tools and functions for solving complex mathematical and computational problems efficiently.

MATLAB provides a vast collection of built-in functions, toolboxes, and libraries for various domains, including signal processing, image processing, control systems, and machine learning. These functions simplify complex tasks and save time in coding. It encompasses the Live Editor, a tool for crafting scripts that integrate code, output, and formatted text within an executable notebook. MATLAB offers extensive tools for data analysis, manipulation, and visualization. Users can create 2D and 3D plots, graphs, and charts to explore and communicate data effectively.

MATLAB offers an interactive and user-friendly environment that allows users to perform computations, run scripts, and visualize data in real-time. Its command-line interface (CLI) enables users to perform tasks interactively, making it an excellent tool for exploring and prototyping. It is written in C language and can support cross platform operating system. [106]

Figure 10 shows the visualization of a network in MATLAB

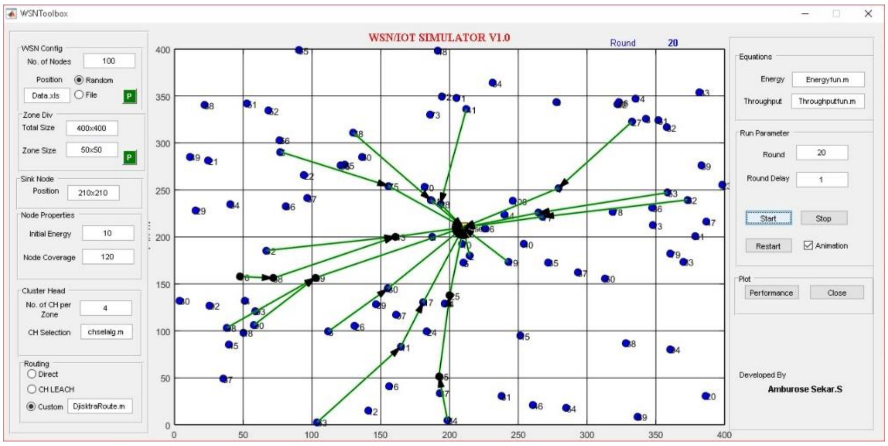


**Figure 10**: MATLAB GUI

Table 7 shows the characteristics of the aforementioned WSN simulators.

| Simulators | Programming Language | O/S | License | Scalability (No of Nodes) | Graphical Support |
|---|---|---|---|---|---|
| NS-2 | C++ / OTCL | Linux, Win | Free | 100 | No or very limited |
| NS-3 | C++ / Python | Linux, Win | Free | 20000 | Limited |
| OMNET++ | C++/NED | Linux, Win | Free for academic use | 1000 | Good visualization |
| OPNET | C++/C | Linux, Win | Free for academic use | ---- | Excellent graphical support |
| MATLAB | C++ | Linux, Win | Commercial | ---- | Excellent graphical support |

**Table 7**: WSN simulators comparison

From the earliest days of WSNs to the cutting-edge technologies of today, the pivotal role that simulation tools play in advancing our understanding of these dynamic and intricate networks has been explored. It is evident that network simulations have become indispensable in the development, evaluation, and optimization of WSNs. These simulations serve as virtual laboratories where researchers and engineers can explore the vast array of challenges and opportunities presented by WSNs, without the constraints and costs of physical deployment.

In the subsequent chapter, the core segment of this thesis is presented, along with the simulation test report for the LEACH protocol and its adaptations.

# CHAPTER 6: Simulation of LEACH protocol and its modifications

## 6.1. Introduction

In the ever-evolving landscape of wireless communication protocols, the choice between different protocols is a critical decision that can significantly impact the performance and efficiency of wireless networks.

Among the plethora of protocols, two prominent contenders often find themselves in the spotlight: LEACH and Threshold LEACH.

However, as technology advances and the demands on wireless networks become more complex, a new variant has emerged, known as Threshold LEACH with Sleep and Awake Scheduler.

Regarding the network model, there are several different models. In light of practical considerations, the following assumptions have been taken into account:

a) All nodes in WSNs are homogeneous with the same attributes,
b) There is no mobility for the nodes,
c) The BS is in a steady pre-defined location.

In order to ensure that MATLAB , the simulator that is used for this comparison, places all nodes in the exact same position on the field, the random number generator *seed* is used (rng(seed)), by setting this in a fixed value before running each simulation. This action should be made before the beginning of the script.

On the other hand, regarding the simulations parameters, the same metrics have been used for all scenarios examined. The different scenarios relate to the number of the nodes, the distribution of the nodes in the network, the size of the network, the location of the BS, and the initial energy of the network nodes.

Following the initial parameters of the network regarding number of the nodes, the spatial configuration and the maximum number of rounds are described:

a) No of nodes = 100
b) Dimensions of the field in coordinates (X=200m ,Y=200m)
c) Location of the BS (X=100m, Y=100m)
d) Maximum number of rounds = 4.000

The common parameters for the energy model of all LEACH protocols are:

- Optimal Election Probability (p) in order to become a node, CH : p =0,1
- Energy required in transmitting 1bit : ETx = $50*10^{-9}$Joules
- Energy required in receiving 1bit : ERx = $50*10^{-9}$Joules
- Initial Energy Nodes: Eo=0,5 Joules
- Amplification coefficient of free-space signal: Efs=$10^{-11}$Joules
- Multi-path fading signal amplification coefficient : Emp=$0{,}0013*10^{-12}$ Joules
- Data Aggregation Energy : EDA=$5*10^{-9}$Joules

For all three protocols the set-up phase is exactly the same, what changes is the steady state phase. For LEACH protocol this phase is based on a random number, while in T-LEACH an extra criterion is taking under consideration, the threshold energy of each node. On the other hand, T-LEACH with sleep/awake scheduler, (TL-LEACH sas), is taking also under consideration the sleep or awake time or each node. So nodes that have inserted in sleep mode are inactive and cannot participate in CH selection, unless they awake.

Before the results of the simulation are presented, a detailed description of this new protocol should be done.

## 6.2. Threshold LEACH with Sleep / Awake Scheduler

This protocol combines the technique of having user defined threshold energy for each node, but also a sleep / awake scheduler. In this updated version, sleep scheduling and duty cycles for non-CH nodes have been introduced. Each round is divided into active slots and sleep slots. During active slots, nodes can transmit and receive data, while in sleep slots, nodes skip the rest of the processing for that round, conserving energy. The activeSlots and totalSlots parameters can be adjusted to control the duty cycle.

The code of this protocol acts as following:

The code begins by initializing various variables, including the threshold with a suitable value, the number of active slots (activeSlots) and the total number of slots (totalSlots) for sleep scheduling. It then calculates the average energy of all alive nodes in the network (avgEnergy) based on the energy levels of the active nodes at the beginning of the round.

The dynamic threshold is then updated using a weighted average approach, considering the previous threshold value and the current average energy. This dynamic threshold will be used to determine which nodes becomes CH.

The fundamental parts of the code are the implementation of sleep / awake scheduling.

The active slots are defined in the code as follow:

a) The code divides each round into a fixed number of slots (`totalSlots`), which can be set based on the desired duty cycle of the nodes.
b) Nodes are considered to be in active slots during the first `activeSlots` slots of each round (`slot < activeSlots`). In active slots, nodes are allowed to transmit and receive data and participate in network activities.

On the other hand, the sleep slots are defined in the code as:

a) The remaining slots after the active slots are considered sleep slots (`slot >= activeSlots`). In these slots, nodes are not required to perform any data transmission or processing, and have the capability to enter a sleep state as a means of conserving energy.
b) Nodes in sleep slots skip the rest of the processing for that round, thus saving energy and reducing unnecessary energy consumption.

Table 8 summarizes the prerequisites for the two situations (sleep / awake) and the impact of the application of these two situations.

| Mode of Nodes | Prerequisites | Impact of node's behavior |
|---|---|---|
| **Active Mode** | slot < activeSlots | In active slots, nodes are allowed to transmit and receive data and participate in network activities. |
| **Sleep Mode** | slot >= activeSlots | In these slots, nodes are not required to perform any data transmission or processing, and they can enter to a sleep state to preserve energy. |

**Table 8**: Prerequisites and impact of both situations in nodes

The sleep scheduling works as below:

The loop iterates through all nodes in the network (in the code n denotes the total number of nodes).

For each node, it checks if the energy level (S5(i).E in the code) is greater than zero, i.e., the node is still active and has remaining energy to participate in the round.

If the node is a non-CH (S5(i).type == 'N'), it applies sleep scheduling and duty cycling logic to conserve energy.

The code calculates the current slot number for the node (slot = mod(r, totalSlots)), where r represents the current round number. This allows cycling through active and sleeping slots.

If the node is in an active slot (slot < activeSlots), it can transmit and receive data during this round. The sleep counter (S5(i).G) for the node is reset to its initial value (round(1/p) - 1), ensuring the node remains active for a fixed number of rounds before going to sleep.

If the node is in a sleep slot (slot >= activeSlots), the code skips the rest of the processing for this round for this node, allowing it to conserve energy by remaining in a sleep state.

For the CH selection, the code performs the following tasks:

The loop iterates through all nodes again to select CHs based on energy and distance metrics.

For each active node, it calculates the distance to the BS (distanceToBS), which is used as a metric for CH selection.

It then calculates a combined metric (selectionMetric) that considers both the remaining energy of the node and its distance to the BS. The weighting factor for the energy and distance metrics can be adjusted by the user to achieve the desired trade-off between the two factors.

If the node's combined metric is greater than the threshold (defined as "threshold" in the code) and the node's sleep counter (S5(i).G) is not positive (indicating the node is not scheduled to sleep this round), the node is selected as a CH.

The code then proceeds to set the node as a CH, updates relevant statistics, and calculates the energy dissipated due to CH selection.

If the node is not selected as a CH, its sleep counter (S5(i).G) is decremented, indicating that the node will go to sleep after the specified number of active rounds.

The loop ends after processing all active nodes in the network for the current round. The process continues for each round of the simulation. Sleep scheduling and duty cycling are applied to non CH nodes, reducing their active participation time in the network, thus saving energy. Meanwhile, CH selection is performed based on a dynamic threshold that balances energy and distance metrics.

Finally all variables are stored in a workspace, from which can be exported to any format for further analysis (.xls , .csv. etc.) At the same time, some metrics are plotted .

## 6.3. Test reports of LEACH simulations and its modifications

Different scenarios relate to the number of the nodes, the distribution of the nodes in the network, the size of the network, the location of the BS, and the initial energy of the network nodes were tested in all protocols. In order to attain improved results, a significant number of repetitions were conducted for each scenario, and the findings related to the network's lifespan are provided in the subsequent tables.**Default Scenario (Scenario A)**

This was the first scenario that took place and included the spatial distribution of 100 nodes (common distribution for all three protocols) in a FOI of 200x200m, where the BS is centrally located at 100x100m and assumed that the lifetime of the network will not exceed 4000 rounds.

The following figures and tables represent the outcome of this scenario.

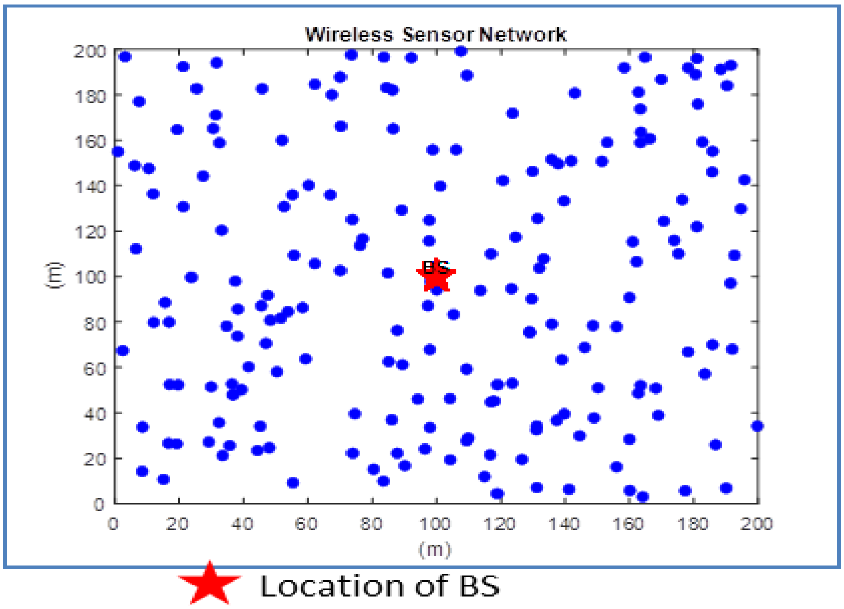


**Figure 11**: Common topology of nodes for three protocols

By using the rng command the deployment of the nodes remain the same for all three protocols and the red star indicates the location of the BS.

The following figure depicts how energy is dissipated through the complement of the maximum number of rounds.

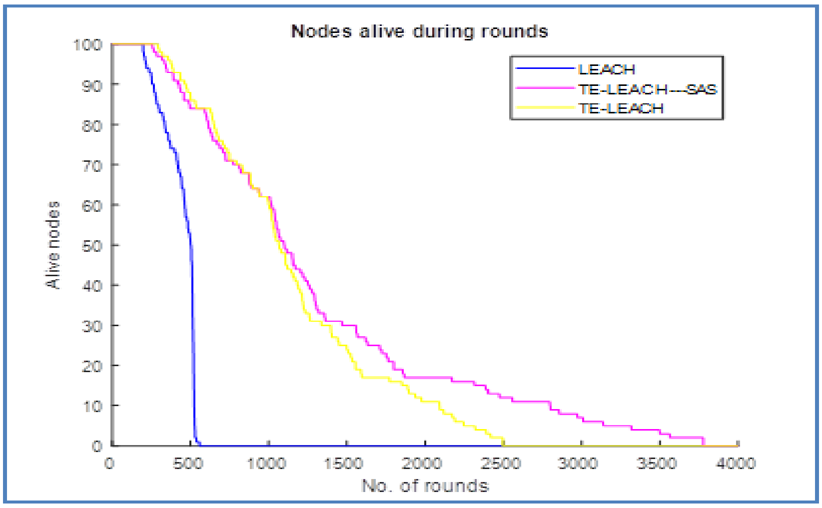


**Figure 12:** Nodes alive during rounds

The blue line indicates the LEACH protocol, the yellow the TE-LEACH protocol and the magenta color the TE-LEACH SAS. From the above graph, the lifetime of the LEACH protocol ends after the completion of 500+ rounds, while nodes that participate at TL-LEACH & TL-LEACH SAS protocol last longer and they are closed to the maximum number of rounds. More specific, the lifetime of TL-LEACH expires at 2.497 rounds and the equivalent of the TL-LEACH SAS at 3.778 rounds.

Table 9 contains a very important metric for the lifetime of the WSN and has to do with the depletion of the rounds through the execution rounds.

| Name of protocol | Depletion of first node (rounds) | Depletion of last node (rounds) |
| --- | --- | --- |
| LEACH | 198 | 559 |
| T-LEACH SAS | 258 | 3.778 |
| T-LEACH | 294 | 2.497 |

**Table 9:** Depletion of rounds through execution rounds

For LEACH protocol the first node dies on 198th round, while the whole WSN dies after 559 rounds. For T-LEACH SAS, the first node dies on 258th round, while it lasts longer from the other protocol. On the other hand, in T-LEACH protocol the first node dies after the completion of 294 rounds, while it lasts almost the same as T-LEACH SAS protocol.

By comparing the aforementioned figures the TL-LEACH SAS lasts 85% more than the classic LEACH protocol and 34% more than the T-LEACH protocol.
In the figure 6.3 & Table 10 the amount of sent data are shown, where the TL-LEACH SAS has sent the biggest amount of bits during the execution.

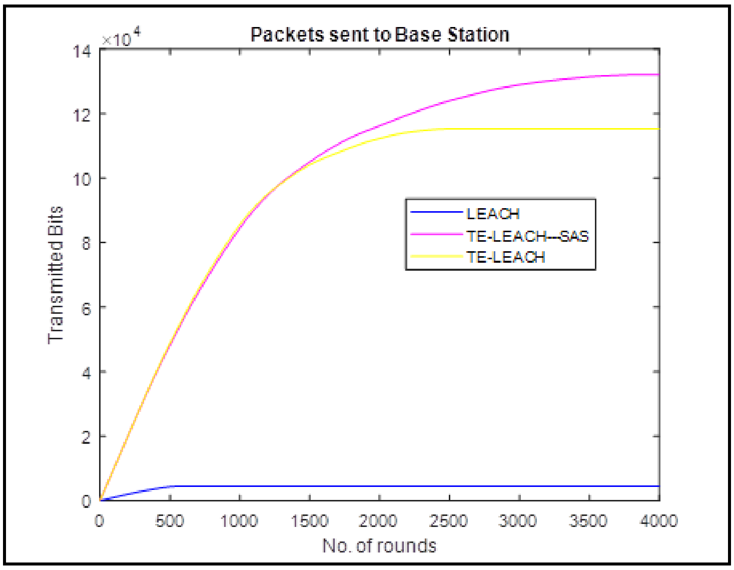


**Figure 13**: Packets sent to BS

| Name of protocol | Packets sent (bits) |
|---|---|
| LEACH | 4.479 |
| T-LEACH SAS | 132.026 |
| T-LEACH | 115.309 |

**Table 10**: Packets sent to BS

### A. Simulation Tests based on BS Location (Scenario B)

As presented in previous chapter a key factor with major impact in the lifetime of the WSN, is the distance between the CHs and the BS, which in the free space model, power usage increases with $d^2$ [107].

In this scenario various location of the BS has been chosen. The following pictures show the various location of the BS.

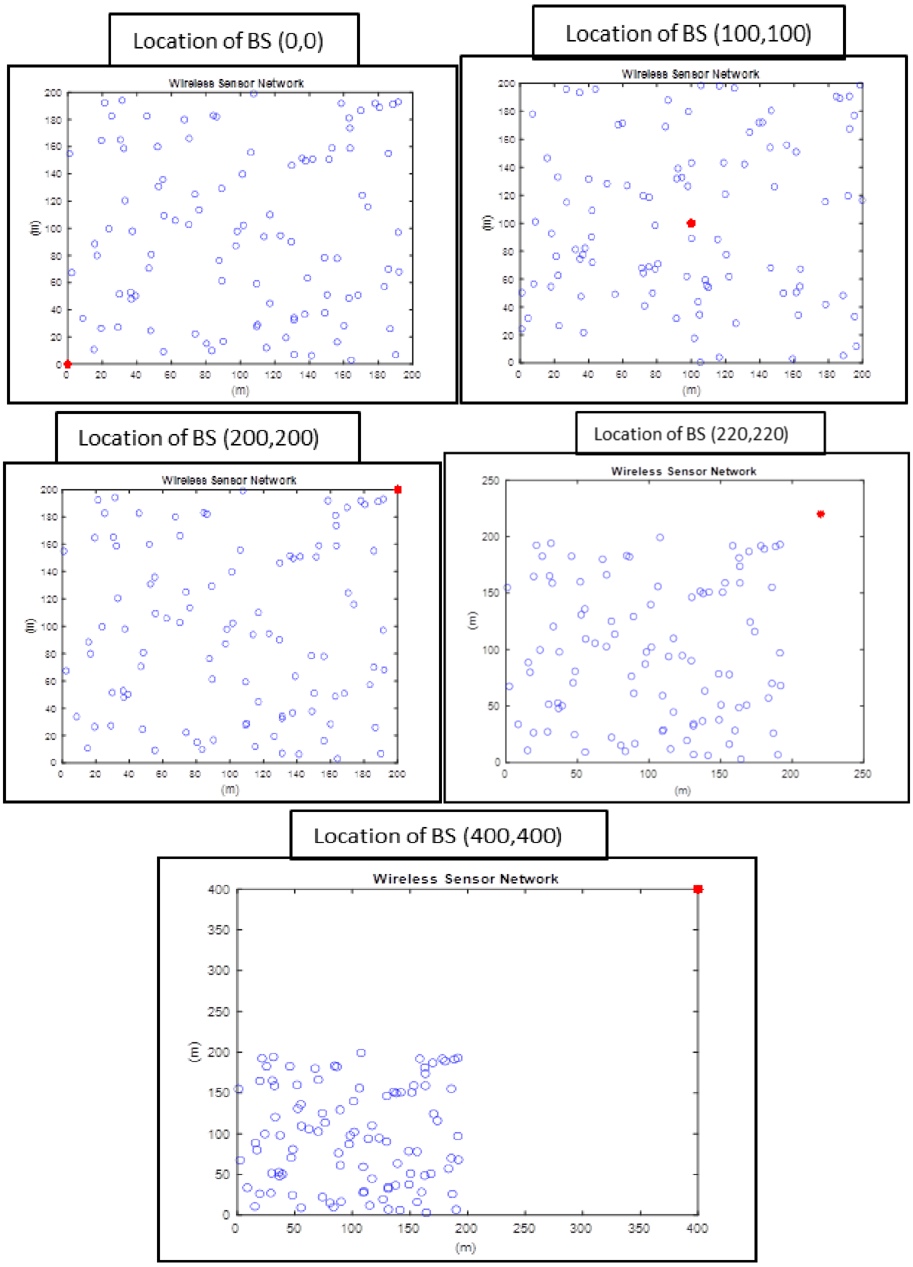


**Figure 14**: Various BS's installation point

In the upper left picture, the BS is located at (0, 0), in the upper right is located at the center of the FOI (Scenario A), in the middle left the BS is located at the edge of the WSN's coverage , while in the two last pictures the BS is located far from the WSN coverage. Especially in the last picture the BS is located at a distance of more than two times the coverage area of the WSN.

It is worth noting that the two last sub-scenarios added extra workload to the simulator and additional time to be executed.

Based on the various location of the BS, the following table was created.

| Location of BS | Name of Protocol | Depletion of first node (rounds) | Depletion of last node (rounds) |
|---|---|---|---|
| (0,0) | LEACH | 84 | 462 |
| | T-LEACH SAS | 15 | 3.364 |
| | T-LEACH | 18 | 2.338 |
| (100,100) | LEACH | 198 | 559 |
| | T-LEACH SAS | 258 | 3.778 |
| | T-LEACH | 294 | 2.497 |
| (200,200) | LEACH | 81 | 546 |
| | T-LEACH SAS | 17 | 3.628 |
| | T-LEACH | 20 | 2.441 |
| out of range (220,220) | LEACH | 61 | 492 |
| | T-LEACH SAS | 11 | 2.428 |
| | T-LEACH | 14 | 1.911 |
| out of range (400,400) | LEACH | N/A | N/A |
| | T-LEACH SAS | N/A | N/A |
| | T-LEACH | N/A | N/A |

**Table 11**: Depletion of rounds based on various BS locations

The above table shows that the location of the BS (BS) in a WSN can have a significant impact on network performance, including energy consumption, coverage, and overall efficiency. The nodes dissipated more energy as BS is getting far away from the coverage of the WSN. Placing the BS closer to the sensor nodes reduces the transmission distance, which can lead to lower energy consumption during data transmission. Nodes can operate at lower power levels when communicating with a nearby BS. This actually proves what is highlighted in the bibliography and explains why none of the 3 protocols can reach the BS.

### B. Simulation Tests based on various node's initial Energy

The initial node energy in a WSN plays a crucial role in determining the network's lifetime and overall performance. The initial energy level of sensor nodes directly affects how long the network can operate effectively before the nodes run out of energy. Nodes with higher initial energy levels can continue functioning for a longer duration before requiring energy replenishment or replacement.

On the other hand, nodes in a WSN consume energy during various activities, such as sensing, processing, and communication. The initial energy level, when divided by the energy consumption rate, gives an estimate of how long a node can actively participate in network operations.

In this scenario, the initial value of energy has been increased and decreased according to the sub-scenarios while the rest of the parameters remain the same.

Table 12 summarizes the results:

| Initial energy of nodes (J) | Name of Protocol | Depletion of first node (rounds) | Depletion of last node (rounds) |
|---|---|---|---|
| 0,005 | LEACH | 1 | 12 |
| | TL-LEACH SAS | 3 | 39 |
| | TL-LEACH | 3 | 25 |
| 0,05 | LEACH | 18 | 71 |
| | TL-LEACH SAS | 26 | 379 |
| | TL-LEACH | 30 | 250 |
| 0,5 | LEACH | 198 | 559 |
| | TL-LEACH SAS | 258 | 3.778 |
| | TL-LEACH | 294 | 2.497 |
| 1 | LEACH | 397 | 1.037 |
| | TL-LEACH SAS | 516 | Still Active |
| | TL-LEACH | 587 | Still Active |

**Table 12:** Impact of initial nodes energy in WSN lifetime

The higher the initial energy of the sensor nodes in a WSN, the longer the WSN lifetime is expected to be. This is because sensor nodes with more initial energy have a greater capacity to perform network operations, including sensing, processing, and communication, before their energy is depleted.

Nodes with more initial energy can actively participate in network activities, such as data transmission and sensing, for a more extended period before their energy is exhausted. This leads to a longer time during which the WSN can perform its intended tasks.

On the other hand, routing protocols often take into account the remaining energy levels of nodes when selecting paths for data transmission. Nodes with higher initial energy may be favored in routing decisions, which can lead to more energy-efficient communication. This explains the reason why TL-LEACH and TL-LEACH SAS, last longer than the classic LEACH does.

### C. Simulation Tests based on various number of nodes

In scenario D, the impact of the impact of network density as expressed by the number of the network nodes spread in network areas having the same dimensions has been studied.

Table 13 depicts the relation between number of nodes and WSN lifetime:

| Number of Nodes | Name of Protocol | Depletion of first node (rounds) | Depletion of last node (rounds) |
|---|---|---|---|
| 50 | LEACH | 243 | 710 |
| | TL-LEACH SAS | 258 | **3.499** |
| | TL-LEACH | 294 | 2.392 |
| 100 | LEACH | 198 | 559 |
| | TL-LEACH SAS | 258 | **3.778** |
| | TL-LEACH | 294 | 2.497 |
| 1.500 | LEACH | 96 | 446 |
| | TL-LEACH SAS | 194 | **3.782** |
| | TL-LEACH | 294 | 2.498 |
| 5.000 | LEACH | 104 | 443 |
| | TL-LEACH SAS | 194 | **3.783** |
| | TL-LEACH | 223 | 2.498 |

**Table 13:** Impact of Number of Nodes in WSN lifetime

The number of nodes in a WSN can have a significant impact on the network's lifetime. For protocol LEACH as the number of nodes in the network increases, the overall energy consumption rate typically increases because more nodes are active, sensing, processing, and communicating data. This can lead to faster energy depletion in individual nodes and, in turn, reduce the network's lifetime. This means that LEACH protocol is ideal for WSN deployment with a limited number of nodes, while TL-LEACH SAS and TL-LEACH is the most suitable for dense WSNs.

# CHAPTER 7:
# Future Challenges and Epilogue

## 7.1. Recapitulation

The central focus of this thesis was to implement a new protocol for WSN regarding the energy efficiency and compared to other already existing and well known protocols. But in order to be this achieved a deep understanding of the classification of energy routing protocol was presented, as well as some indicative but highly rated protocols of each category. In addition, this thesis focused more on LEACH protocol and its successors and a detailed presentation between them was occurred. Furthermore, some of the most known energy conservation techniques for WSN were presented.

After a short introduction in network simulators, a comparison between classic LEACH protocol and TL-LEACH and TL-LEACH SAS took place through MATLAB.

The research work conducted in this thesis has been partially presented in [108] and also contributed to [109] and [110].

## 7.2. Concluding remarks

WSNs find utility across a diverse array of industries and fields owing to their capacity to acquire real-time data from remote or inaccessible locations. Environmental monitoring, agriculture activities, industrial automation and control, healthcare issues, etc. are some of the common and emerging uses of WSNs. As technology continues to advance, new and innovative uses for WSNs are continually emerging, making them a versatile tool for data collection and monitoring in a variety of fields.

Despite their numerous applications and advantages, WSNs face several challenges and problems, some of which can limit their effectiveness and reliability.

One major challenge is the energy conservation. The constrained energy resources of sensor nodes make it essential to develop strategies and protocols that maximize network lifetime. The introduction of LEACH protocol marked a pivotal moment in the development of WSNs. LEACH protocol is indeed one of the pioneering and widely recognized protocols designed for energy conservation in WSNs. LEACH pioneered the concept of data clustering to achieve a more equitable distribution of the energy load among sensor nodes, ultimately leading to an extension of the network's lifespan. LEACH's innovative approach to energy-efficient clustering and data aggregation laid the foundation for numerous research efforts aimed at optimizing WSN performance, energy efficiency, and network longevity. So, over the years, LEACH inspired a series of successor protocols, each designed to address specific challenges and adapt to varying WSN scenarios. These successors have contributed to the growth and adaptability of WSNs. These protocols, along with many others, have demonstrated the resilience and adaptability of WSNs in the face of evolving challenges.

While LEACH is a highly influential protocol for energy conservation in WSNs, it's worth noting that there have been subsequent improvements and variations of the LEACH protocol, such as LEACH-C, TEEN, and HEED, which address some of its limitations and adapt it to specific application scenarios. Selecting the most appropriate protocol for a WSN deployment is a critical decision and depends on the specific requirements and constraints of the given scenario. WSNs can serve a wide range of applications, and the choice of protocol should align with the objectives and operational conditions of the deployment.

For all the aforementioned reasons, a comparative analysis between classic LEACH and its successors TL-LEACH & TL-LEACH with sleep / awake scheduling was performed. The choice between LEACH, Threshold LEACH, and Threshold LEACH with Sleep-Awake Scheduling depends on the specific requirements and constraints of the WSN application. Threshold LEACH offers a more energy-efficient version of LEACH, while the addition of sleep-awake scheduling further enhances energy savings and network lifetime.

However, implementing sleep-awake scheduling may introduce additional complexity and synchronization challenges. Therefore, the selection should consider the trade-offs between energy efficiency, complexity, and the specific needs of the WSN deployment.

## 7.3. Research projects in WSN

As WSNs continue to mature, they also confront a series of open research challenges that beckon for innovative solutions. These challenges underscore the dynamic nature of WSNs and emphasize the need for continuous exploration and discovery in this field. From the persistent quest for energy-efficient protocols to the intricacies of data management, security, and scalability, the landscape of WSNs is rife with complexity and opportunity.

Each challenge encapsulates not only a problem to be solved but also a potential breakthrough that could redefine the capabilities of WSNs. Many ongoing projects are dedicated to the development of communication protocols and management services that cater to the particular needs of sensor nodes, including constraints like limited power, processing capacity, and storage. Within the realm of WSN, prominent areas of research revolve around topics such as topology creation, control, and maintenance. [111]

The *Smart Santander Project* as outlined in [112] has been implemented to support a wide array of applications and services for a smart city. This pioneering experimental facility is characterized by its considerable size, openness, and adaptability, which enable it to foster collaboration both horizontally and vertically with other experimental facilities. It serves as a catalyst for the development of novel applications, accommodating users of diverse backgrounds, including those engaged in advanced research on IoT technologies and real-world acceptability tests. The project's vision entails the deployment of 20,000 sensors across various locations, with significant representation in Belgrade, Guildford, Lübeck, and Santander, featuring 12,000 sensors, and utilizing a diverse range of technologies.

The *CodeBlue* project conducted at Harvard University is dedicated to the exploration of WSNs for medical applications within disaster scenarios. [113] These applications encompass a broad spectrum of healthcare needs, including pre-hospital and in-hospital emergency care, disaster response, and the rehabilitation of stroke patients.

In contrast, the *Mercury project* specifically concentrates on the development of wearable sensors designed to continuously monitor patients' vital signs in their day-to-day lives. This research at Harvard University represents a vital endeavor in leveraging WSNs to enhance healthcare outcomes and address medical challenges in both disaster and routine settings. [114]

The *GlacsWeb* project is an initiative that involves the placement of sensors within glaciers to observe and track the movement or drifting behavior of these icy formations. This project aims to gain insights into glacier dynamics and behaviors, offering valuable data for scientific research and environmental monitoring. [115]

The *eDIANA* project is dedicated to addressing the imperative of enhancing energy efficiency in buildings by implementing innovative solutions that rely on embedded systems. The central approach of eDIANA revolves around optimizing the use of resources, with a primary focus on conserving energy as a limited resource. This strategy prioritizes greater flexibility in resource allocation and improving situational awareness for both residents and the proprietors of services and infrastructure. By doing so, the project seeks to advance energy efficiency in building operations, resulting in more sustainable and resource-conscious practices [116].

*European WSN project SecureWSN* [117] started at the Technische Universität München (TUM), continued at the University of Zurich (UZH), and now continues at the Research Institute CODE is an IoT Framework supporting constrained IoT platforms like sensor devices from different vendors. SecureWSN offers different security algorithms for efficient and secure communication within the sensor networks to the sink. The sink is a framework called CoMaDa offering users configuration, management and data handling functionality for deployed network. Further a mobile framework is included in SecureWSN offering the user to give authorized access to collected data of deployed network and allows authorized users to query immediate data collection (e.g., in emergency cases or in absence from home).

Numerous projects funded by the EU are part of the Horizon Europe Framework Programme (HORIZON), which is the EU's principal research and innovation funding program [118]. As an example, the project HORIZON-CL3-2023-CS-01-01 is specifically focused on the proactive and automated detection, analysis, and mitigation of cybersecurity attacks within cloud environments, at the edge, in the context of operational technology (OT), IoT deployments, and across application domains such as smart cities. Ensuring comprehensive security from end to end and emphasizing user-centric privacy within complex distributed platforms demands substantial endeavors to effectively tackle security threats and vulnerabilities across the entire platform ecosystem.

The *PERPS* project, as introduced in [119], puts forth a pioneering strategy for energy harvesting systems. It offers a comprehensive perspective on crafting a sustainable and inventive technical solution that ensures the perpetual operation of Internet of Things (IoT) edge nodes as well as portable and wearable electronic devices. This is achieved by incorporating ultra-low power circuit designs, which are tailored to maximize efficiency and, consequently, enhance overall performance. The project's ultimate aim is to create a self-sustaining energy system that ensures the continuous operation of these devices.

*The ECO4RUPA* project has introduced an all-encompassing and smart routing ecosystem, which employs a network of affordable air quality (AQ) sensors. This system is further enhanced by leveraging 5G communications and integrating data from official AQ monitoring stations. Spatial interpolation techniques are applied to improve the spatial resolution of the collected AQ data [120].

## 7.4. Future Challenges

In an age where connectivity and data have become the lifeblood of our digital existence, WSNs have emerged as a pivotal technology, poised to play a transformative role in shaping our future. These networks, comprised of numerous tiny, self-contained sensor nodes, communicate wirelessly to collect and transmit data from the physical world. From environmental monitoring to smart cities, agriculture to healthcare, the applications of WSNs are vast and profound.

As technology steps into the future, a host of challenges must be addressed to harness the full potential of WSNs. These challenges span technical, operational, and ethical dimensions, and they promise to shape the trajectory of this technology in the years to come.

- *Scalability*: One of the foremost challenges in the world of WSNs is scalability. As networks are envisioned with thousands, even millions of nodes, the need for efficient protocols and algorithms to manage this vast scale becomes apparent. How the seamless communication, data management, and energy efficiency, connectivity issues with heterogeneous networks, interoperability issues in networks of such unprecedented size can be ensured. [121]
- *Energy Efficiency:* Sensor nodes in WSNs are often battery-powered and deployed in remote or inaccessible locations. Prolonging the lifespan of these nodes is crucial. Developing energy-efficient algorithms, low-power hardware, and exploring energy harvesting solutions are vital endeavors. [122]
- *Reliability and Fault tolerance:* WSNs are often located in harsh and dynamic environments, where sensor nodes can fail due to various reasons. Ensuring reliable data collection and communication in the face of node failures and network disruptions remains a complex challenge [123].
- *Quality of Service (QoS):* Given their interaction with the environment, the characteristics of WSNs often diverge from those of conventional data networks. Various applications within WSNs exhibit diverse QoS requirements. Striking the

right balance between ensuring the necessary level of service for applications, such as healthcare or critical infrastructure monitoring, while also efficiently managing network resources is a delicate and complex task [124].

- *Data Security and Privacy:* As WSNs collect and transmit sensitive data, ensuring the security and privacy of this information is paramount. Safeguarding against unauthorized access, data breaches, and eavesdropping presents significant challenges, particularly in resource-constrained environments [125].

The future of WSNs holds immense promise but also presents formidable challenges. While the challenges described in this paragraph are indicative, they are significant and cannot be underestimated. However, it's crucial to view these challenges as opportunities to reshape the potential of WSNs. Overcoming these obstacles won't just result in longer-lasting sensor nodes and improved network performance; it will also play a pivotal role in fostering a more sustainable and interconnected future.

In this future, where energy efficiency is harmoniously merged with robust routing protocols, WSNs can continue to play a pivotal role in shaping our world. They have the potential to drive innovations in healthcare, environmental monitoring, industrial automation, and more, making our lives safer, more efficient, and environmentally conscious. Achieving this vision will require concerted and collaborative efforts from a community of researchers, engineers, and stakeholders who are committed to pushing the boundaries of WSN technology.

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