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Πρόγραμμα Μεταπτυχιακών Σπουδών
Ηλεκτρικές & Ηλεκτρονικές Επιστήμες μέσω Έρευνας

Master of Science By Research in
Electrical & Electronics Engineering

ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΜΕΘΟΔΟΛΟΓΙΕΣ ΕΞΟΙΚΟΝΟΜΗΣΗΣ ΕΝΕΡΓΕΙΑΣ ΣΕ ΑΣΥΡΜΑΤΑ ΔΙΚΤΥΑ ΑΙΣΘΗΤΗΡΩΝ

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ΑΘΗΝΑ-ΑΙΓΑΛΕΩ, ΙΟΥΛΙΟΣ 2023

ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
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Master of Science By Research in
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MSc Thesis

ENERGY SAVING METHODOLOGIES IN WIRELESS SENSOR NETWORKS

Student: EMMANOUIL ANDREAS EVANGELAKOS, Registration Number 0058
MSc Thesis Supervisor: DIONISIOS KANDRIS, Professor

ATHENS-EGALEO, JULY 2023

Η Μεταπτυχιακή Διπλωματική Εργασία έγινε αποδεκτή, εξετάστηκε και βαθμολογήθηκε από την εξής τριμελή εξεταστική επιτροπή:

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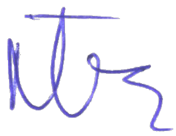
XENOFON DIONYSIOS KANDRIS Digitally signed by XENOFON DIONYSIOS KANDRIS Date: 2023.07.17 13:07:18 +03'00'	Maria Ragkousi Digitally signed by Maria Ragkousi Date: 2023.07.17 17:05:29 +03'00'	 Digitally signed by Nikolaos-Alexandros Tatlas Date: 2023.07.18 10:58:31 +03'00'
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Ο κάτωθι υπογεγραμμένος Εμμανουήλ Ανδρέας Ευαγγελάκος του Γρηγορίου, με αριθμό μητρώου MSCRES-0058 φοιτητής του Προγράμματος Μεταπτυχιακών Σπουδών «Ηλεκτρικές και Ηλεκτρονικές Επιστήμες μέσω Έρευνας» του Τμήματος Ηλεκτρολόγων και Ηλεκτρονικών Μηχανικών της Σχολής Μηχανικών του Πανεπιστημίου Δυτικής Αττικής, δηλώνω ότι:

«Είμαι συγγραφέας αυτής της μεταπτυχιακής διπλωματικής εργασίας και κάθε βοήθεια την οποία είχα για την προετοιμασία της, είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος. Τέλος, βεβαιώνω ότι η εργασία αυτή δεν έχει κατατεθεί στο πλαίσιο των απαιτήσεων για τη λήψη άλλου τίτλου σπουδών ή επαγγελματικής πιστοποίησης πλην του παρόντος.

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

Ο Δηλών

Εμμανουήλ Ανδρέας Ευαγγελάκος

ABSTRACT

Energy efficiency is the major issue that arises in Wireless Sensor Networks (WSNs). Batteries that are typically the main power source of a WSN have a restricted lifetime. Hence, energy conservation in WSNs is a rather challenging task. Energy saving can be achieved through the implementation of appropriate techniques that aim to preserve the energy of sensor nodes for greater periods of time and minimize the amount of the consumed energy during nodes sensing, processing, and data transmitting tasks. This thesis aims to analytically examine all existing hardware-based and algorithm-based mechanisms of this kind. Among these mechanisms, energy efficient routing is one that could lead to energy sustainability of WSNs. Several energy efficient routing protocols have been proposed throughout the years, and LEACH protocol as one of the initially developed protocols for WSNs attracts the interest of many researchers, leading to the development of its successors. In this thesis, some modifications of LEACH protocol were developed and compared to it to evaluate their operation.

In chapter 1, the architecture of WSNs, their applications and their types are described. Moreover, not only the causes of energy consumption in WSNs are explained but also all (i.e. 48) mechanisms that have been proposed in order to extend the lifetime of nodes in WSNs are analyzed.

Chapter 2, explains the certain weaknesses, disadvantages and problems that are incorporated into the mechanisms for energy sustainability of WSNs, which obstruct their successful deployment and thus pose corresponding challenges.

Chapter 3, focuses on the hierarchical routing techniques and presents one of the most significant protocols of this type, i.e. LEACH protocol, which is one of the initially developed protocols of this kind along with some of its descendant protocols.

Chapter 4, constitutes the practical part of this thesis, in which simulations of different network deployment scenarios using the LEACH protocol have been conducted. Furthermore, three modifications are developed and compared to LEACH and LEACH-B protocols and their performance is evaluated.

Finally, in Chapter 5, conclusions are drawn and future research challenges are discussed.

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TABLE OF CONTENTS

CHAPTER 1:
Wireless Sensor Networks and Energy Saving Techniques

1.1 Introduction

Wireless Sensor (WSN) is a set of several (few tens or even thousands) spatially dispersed and wirelessly linked devices, called sensor nodes or simply nodes, along with at least one sink node that is called base station (BS) [1]. Nodes aim to not only monitor and collect information related to the ambient conditions that exist in a field of Network interest (FoI) but also process and finally exchange the relative data with other nodes and the BS [2]. The BS is the master node that controls the network that it belongs to, aggregates the data from the nodes and functions as the interconnection point between the network and its end user, given that it is also responsible for the data transmission [3]. The architecture of a typical WSN is illustrated in Figure 1.

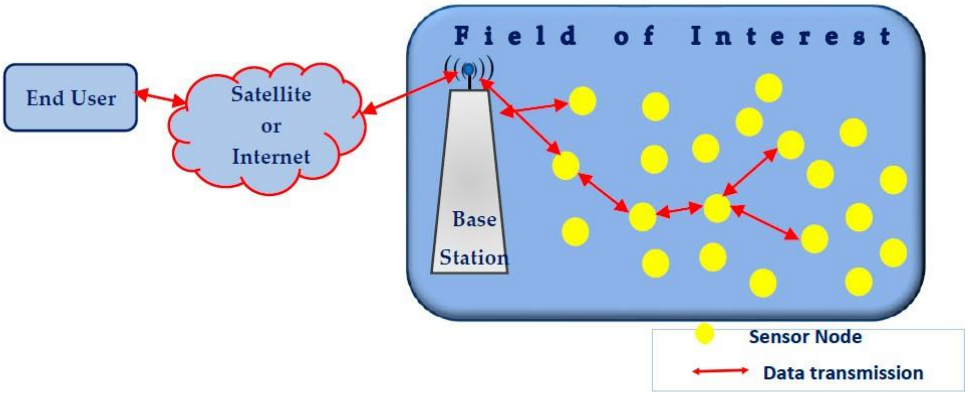

Figure 1: Typical architecture of a wireless sensor network.

1.2 Categories and Types of Wireless Sensor Networks

WSNs are distinguished in two basic categories based on their infrastructure: the *structured* and the *unstructured* wireless sensor networks. In a structured WSN, sensor nodes are distributed in a deterministic manner, at predefined-fixed locations [4] into the network's field. In this category, fewer nodes could be used to provide sufficient coverage since they are deployed in specific locations [2]. Contrarily, a network with a dense amount of randomly located sensor nodes, is defined as an unstructured WSN. Such networks are usually deployed in inhospitable environments where the human intervention is not feasible (e.g., areas where a nuclear accident has occurred). Unlike structured networks that can be easily maintained, the maintenance of unstructured WSNs is usually not achievable, because of their density and the inaccessibility of their deployment areas.

Depending on their field of use, WSNs can be divided into five basic types: Terrestrial, Underwater, Underground, Mobile and Multimedia WSNs [5].

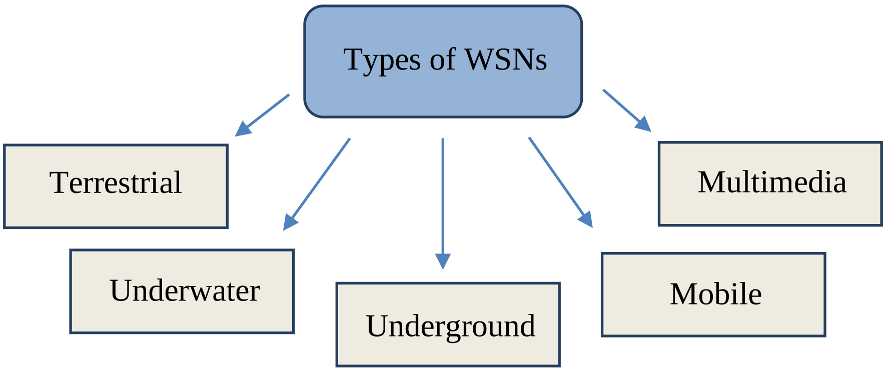

Figure 2: Types of wireless sensor networks.

1.3 Applications of Wireless Sensor Networks

The very first applications of WSNs date back to 1950 and exclusively served military purposes. Nowadays WSNs as a continuously growing technology, are widely used and are able to cover an extensive variety of applications in numerous human activities. Pursuant to their field of use, WSNs are distinguished in six main categories [6]: military, health, urban, environmental, flora & fauna and industrial. Each one of these is divided into diverse subcategories.

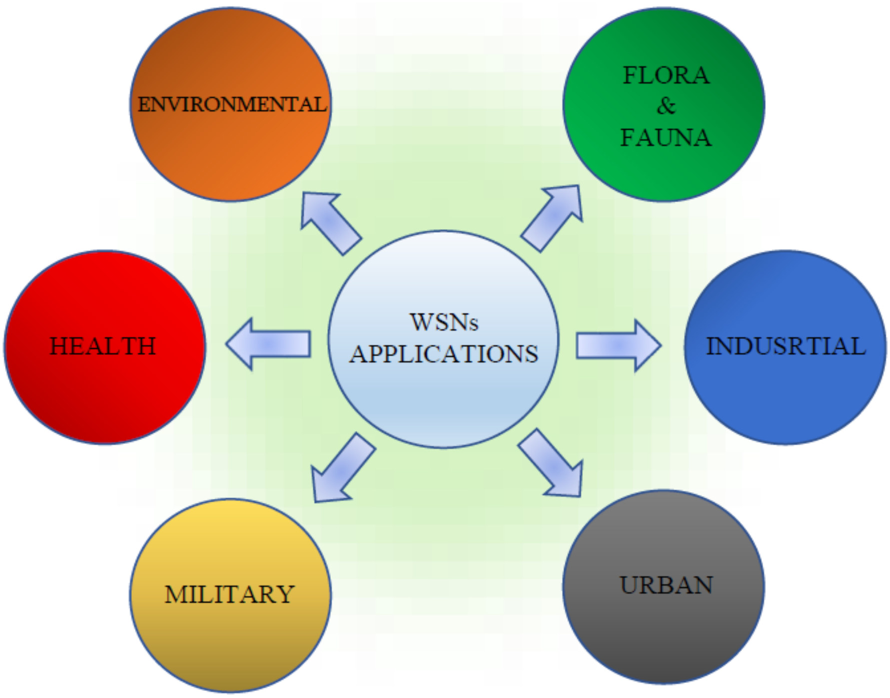

Figure 3: Applications of wireless sensor networks.

In the military domain, WSNs are utilized for: i) monitoring the status of facilities, equipment, vehicles, ammunition and even the deployment of enemy troops in a battlefield, ii) surveilling battlefields, routes, and paths, iii) recognizing and targeting enemies, iv) assessing the damages occurred in a battle, v) detecting nuclear, chemical, biological attacks and more. Typical sensors used in applications such as the aforementioned, are acoustic, infrared, laser, RADAR, vibration, chemical, biological, and toxic material detection sensors.

In the domain of health, WSN are mostly employed to monitor patients and report their physiological data and indications (e.g., body's temperature, heartbeats blood pressure etc.). Such tasks can be carried out by utilizing wearable devices with embedded biomedical sensors. Moreover, WSNs are used to track and supervise patients or doctors within the facilities of a hospital, or to remotely diagnose the patients' health status regardless of their location. Commonly used sensors on the above applications are biomedical, temperature, motion, humidity, and RF sensors.

The use of WSNs in urban environments, covers a wide range of applications that can be summarized in four basic categories: smart homes, smart cities, transportation, and structural health [6]. Monitoring of vehicle traffic, assets and smart devices operating in smart homes are some of the most common urban applications. WSNs can facilitate processes such as tracking vehicles, managing parking areas, identifying parking spots, detecting flooded roads or tunnels, observing fatigue in buildings and so on.

Wireless sensor networks are also deployed in order to monitor environmental conditions in hostile areas. Various applications have been developed to monitor and evaluate the quality of the drinking or oceanic water, prevent the pollution of seas, the disaster of underwater flora and fauna and more. In addition, WSN applications are also used in air quality monitoring applications and in emergency alerting of natural disasters, such as fire outbreaks in forests, volcanic or seismic activities or detection of physical phenomena such as tsunamis.

WSNs are being employed in flora and fauna applications, such as greenhouse and farming monitoring, as well as livestock farming. The main objectives of WSNs used in this domain are to ensure the sustenance of optimum environmental conditions (temperature, humidity, air pressure, light intensity etc.) in a greenhouse, to monitor and coordinate the fertilization and irrigation of fields, to observe and decompose animals' behavior, to identify or track animals and to collect data regarding their health in order to prevent potential diseases [6].

The presence of WSNs in industrial applications is conducive to the efficient handling of related issues, since it is possible to monitor the operation and condition of the machinery used in industrial environments by utilizing optical, corrosion or heat sensors. Furthermore, WSNs can offer navigational details from the sensing areas to robots so as to follow the most suitable path and reach the desired location of action. WSNs can also prevent accidents that may occur in industries, such as a fire outbreak, machinery damages that could affect the process of an industry's production and more.

1.4 Main Drawback of WSNs and Categorization of Energy Saving Methods

Despite the evident advantages that WSNs offer in a constantly increasing range of human activities, their use is obstructed due to the inborn constraints of wireless communications and the limited resources of the nodes. Actually, the main imperfection of WSNs is the particularly constrained energy adequacy of their nodes [7]. It is initiated by the fact that nodes are powered by batteries of restricted capacity that are difficult or even impossible to recharge or replace. Thus, the operational time of WSN nodes is limited and consequently the overall network lifespan is restricted.

So, the attainment of energy conservation is an issue of critical importance for WSNs and that is why numerous research methods have been proposed by researchers that pursue energy sustainability [8-14]. In this thesis, as illustrated in Figure 4, energy sustainability methods are classified into two main categories, i.e., the hardware-based methods and the algorithm-based methods.

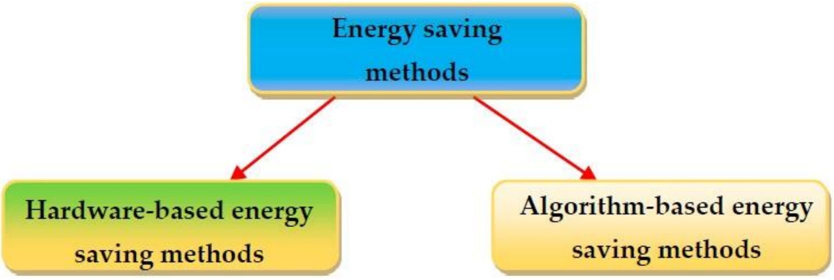

Figure 4: Categorization of energy sustainability mechanisms.

1.5 Consumption and Waste of Energy in WSNs

As mentioned above, in most cases sensor nodes in WSNs have a limited lifetime because of their restricted energy residues. For this reason, the achievement of energy conservation during the obligatory tasks of nodes (i.e., sensing, receiving, transmitting, and processing) is necessitated. Even more so, the elimination of every cause of energy waste is imperative.

Actually, the main causes of energy waste in WSNs are [9]:

- Idle listening, i.e., listening to a communication channel, which is idle, with the intention of receiving possible incoming messages;
- Overhearing, i.e., when a node takes delivery of packets that are intended to be received by other nodes;
- Packet collision, i.e., the conflict caused to the messages that arrive at a node simultaneously which necessitates the rejection of them and their retransmission;
- Interference, i.e., the signals intended to be wirelessly received by a node are modified in a disruptive way due to the addition of other unwanted signals;
- Control packet overhead, i.e., the overhead caused by the excessive use of packets that synchronize data transmission without having data themselves;
- Over-emitting, i.e., the case that a node transmits data packets while the corresponding receiver node is not available to receive them.

1.6 Hardware-Based Energy Sustainability in WSNs

1.6.1 The Architecture of Wireless Sensor Nodes

Each sensor node of a WSN is a Micro Electromechanical system (MEMS) [1, 15], which is composed of four main and two optional subsystems, as illustrated in Figure 5.

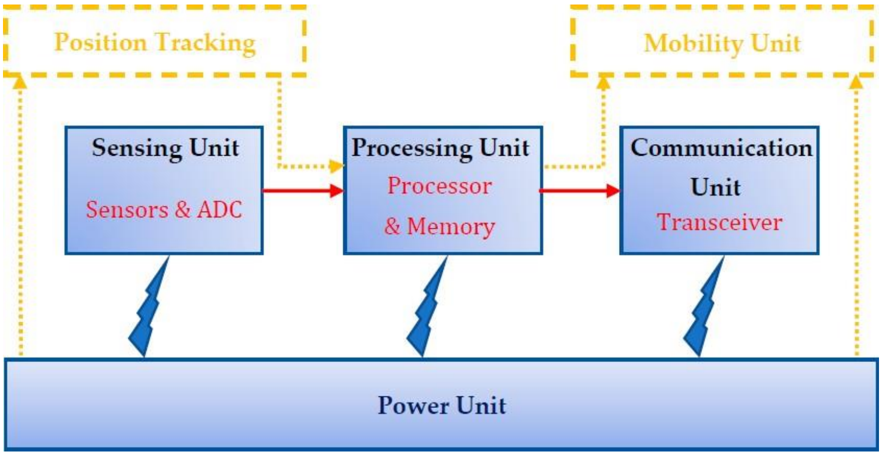

Figure 5: Typical architecture of a wireless sensor node.

The basic subsystems of a node are:

- The power unit, of which the battery is the main and most commonly used part. Solar panels could also be used as a secondary energy source to a node [3];
- The sensing unit that contains one or more analog or digital sensors and an analog to digital converter (ADC);
- The central processing unit (CPU), which comprises a microprocessor or microcontroller, along with its memory and its main purpose is to aggregate, store and process the data recorded from sensors;
- The communication unit, which is responsible for the transmission of the produced data to other nodes or to the base station. The communication unit usually contains a wireless radiofrequency (RF) transceiver. Moreover, devices for communication through optical, or infrared signals may be used.

A sensor node may also contain, as optional subsystems, a position tracking unit, which monitors the current location of this node, and a mobility unit, which provides the node the ability to be transportable [2].

Summarily, the sensing unit of a sensor node is triggered by an occurring event in its adjacent environment. The ADC converts the signals to electric signals that are handled by the processing unit. Once the processing procedure is completed, the produced data can be wirelessly transmitted to neighboring nodes or/and the BS.

1.6.2 Hardware-Based Methods for Energy Sustainability

As illustrated in Figure 6, Hardware-based approaches for energy sustainability focus on the selection of the optimum hardware components that should be embedded in a sensor node, the management of their operation, and the use of energy harvesting and transference methods [8-14].

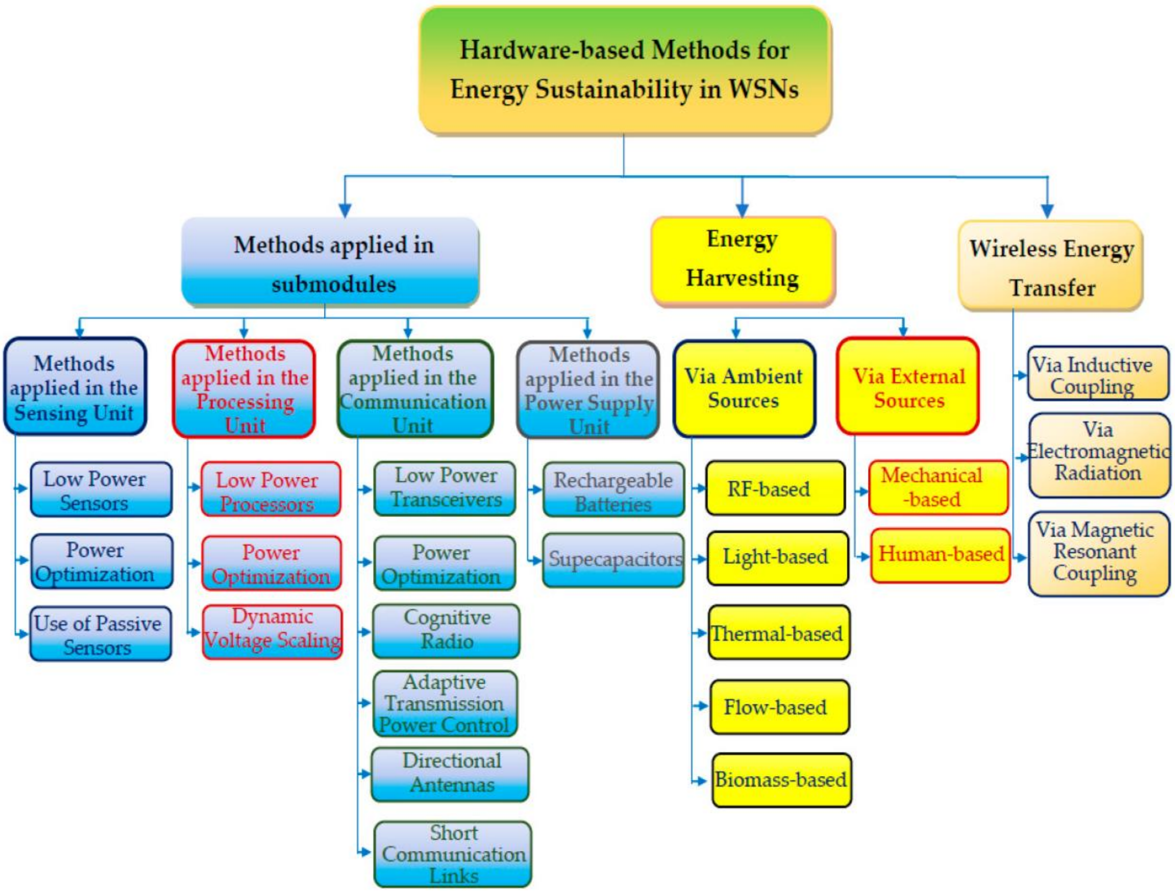

Figure 6: Categorization of hardware-based methods for energy sustainability in WSNs.

1.6.2.1 Energy Saving Methods applied in Submodules

When referring to the main submodules of nodes (i.e., sensors, processors, and transceivers) the utilization of low-power MEMS is necessitated in order to achieve energy saving [1-3, 15]. Moreover, the power of a sensor node can be managed by hardware scaling methods, which are used to handle the settings and the configuration of the hardware in nodes' submodules. When engaging with such methods, the voltage, the frequency, and the rate can be adjusted according to the application's requirements to limit energy consumption. Furthermore, methods such as system power optimization aim at putting the node in sleep mode while not in operation to avoid energy depletion.

Actually, several methods may be applied in each one of the submodules of nodes:

- While designing the Sensing Unit, the type of the application WSN is intended to be used in, needs to be considered in order to choose the appropriate sensors and converters [10, 13].
  - The selection of low power sensor units contributes to the energy conservation of the overall sensor node;
  - The ability to promptly control the operations of sensors (e.g., turning on and off), as well as its quick response time to irritations and its low duty cycle can lead to energy saving;

- Additionally, instead of active sensors, passive sensors may be used. Such devices do not contain any piece of active circuits. For this reason, they use not exterior energy supplies. Actually, they are not powered at all. Instead, they receive incoming signals that they are reflected backwards along with the sensed information [16].

- The design of the central Processing Unit is related to the choice of the optimum microprocessors and microcontrollers (MCUs) [8, 10].
  - Low-power processors offer low frequency clock choices, consume lower currents and are able to operate using lower voltages. In addition, it is critical to avoid implementing a huge number of features and peripherals, since the greater the amount is, the higher the power consumption becomes;
  - Microprocessors, mostly support different modes of operation, such as, active, idle and sleep mode for clearer power management objectives;
  - Furthermore, dynamic voltage scaling (DVS) method frequently applies in processors during their operation in active status in order to lessen the energy consumption levels [17, 18]. Usually, microprocessors do not operate continually at their highest computational power, due to the fact that the work load of each task varies. Thus, the use of DVS method provides energy efficiency to sensor nodes by adjusting both the voltage of the processor and operating frequency dynamically according to the demands of the momentary processing tasks.

- The selection of appropriate transceivers to be integrated in the communication unitof the sensor nodes is extremely helpful in order to achieve energy conservation.
  - The use of low power transceivers is extremely helpful in order to reduce energy consumption [8];
  - Putting the transceiver in sleep mode while there are no communication needs, or using Adaptive Transmission Power Control can also save energy;
  - The use of Cognitive Radio (CR), i.e., an intelligent radio that enables the dynamic selection of the most suitable radio channel can lead to network's energy conservation [10]. This selection depends on the transmit power, the data rate, the duty cycle, and the modulation required by the existing conditions;
  - In the so-called Adaptive Transmission Power Control method, the power required for data transmission is estimated based on the distances among nodes [8]. Additionally, the power levels of the transmitter are adjusted according to the needs of each application, in order to limit the energy consumption [13];
  - In addition, directional antennas may be used. Such antennas are able to both send and receive signals in one direction. Subsequently, they consume lower amounts of power comparatively to omnidirectional antennas that transmit towards many and probably undesired directions and consequently cause higher energy consumption [10];
  - Moreover, energy conservation depends on the way the nodes are deployed, the distance between them and the power needed for data transmission. In

fact, in networks with dense deployment, nodes can communicate with nearby allocated nodes by using small communication links. This way, the transferred data reach their final destination by exploiting multi-hop paths, which results in the consumption of low power levels of each node. Contrariwise, in networks with sparse deployment in which single-hop communication applies, the transmission power and consequently the overall energy dissipation is greater [10];

- Regarding the power supply unit of sensor nodes, small batteries with restricted capacity [11] are typically used as power sources. The amount of the stored energy while a battery is fully charged is characterized as its capacity. There are different types of batteries used in WSNs, and some of the most commonly used are the Alkaline, the Lithium-Ion (Li-ion) and the Nickel Metal Hydride (NiMH) batteries. Of course, all types of batteries have an extremely limited lifetime. For this reason, the use of rechargeable batteries or supercapacitors is a better alternative.
  - In WSNs where the recharge of the batteries of the nodes is feasible, the usage of rechargeable batteries can considerably prolong the operational lifespan of the nodes and the overall network. Additionally, due to their high energy density, rechargeable batteries are suitable for WSNs utilizing energy harvesting implementations. Specifically, the density of NiMH batteries is 60-80 Wh/kg and that of lithium batteries is 120-140 Wh/kg, while their lifetime varies between 300-500 and 500-1000 recharge cycles, respectively [8]. In the cases where battery recharge is difficult to perform, techniques that aim at either estimating [19] or prolonging [20] the remaining battery lifetime may be used;
  - Supercapacitors are capacitors having higher capacitance with lower voltage limits when compared to typical capacitors. They have grown into practical alternatives of power sources in WSNs nodes due to their energy density levels that range between 1-10 Wh/kg, and their smaller size in comparison with batteries. Thus, an even long-lasting lifespan of the sensor nodes could be achieved by replacing the non-rechargeable batteries of sensor nodes used in harvesting systems with supercapacitors as means of energy storage [8].

1.6.2.2 Energy Harvesting

Generally, energy harvesting is the process by which energy is captured and stored in order to empower small electronic devices. In WSNs, energy harvesting is achieved using energy scavenging systems that can be attached in the sensor nodes [21, 22]. Power management modules (PMM) are usually integrated in these energy harvesting systems in order to increase the harvested power level and to restrict the energy mismatches between the harvester and the node. Typically, the harvesting process entails an energy source, a harvester or harvesting system, and standalone nodes or nodes with embedded energy storage devices [8, 23]. The overall energy harvesting energy process is illustrated in Figure 7.

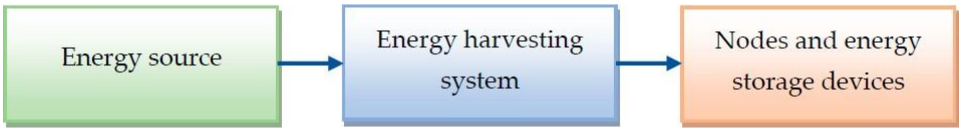

Figure 7: Overview of energy harvesting process.

Specifically, energy harvesting can be performed by taking advantage of either ambient or external sources. Ambient sources of energy are almost permanently available in the surrounding environment of the nodes, while external sources of energy are especially set up for energy scavenging purposes [24, 25].

- According to the specific type of the physical quantity that is used, energy harvesting via ambient sources can be further classified as: RF-based, light-based, thermal-based, flow-based, and biomass-based [22, 23].
    - RF-based energy harvesting makes use of radio frequency (RF) waves that may derive from wirelessly emitted signals coming from the BS, television, radio, Wi-Fi, or mobile devices. Such RF waves are initially captured by the nodes via either the receiver that they use for their wireless communication or another radio antenna that is dedicated only for energy scavenging. Next, the RF waves captured are converted into DC electricity [24, 26];
    - In case there is the ability to capture light energy from either sunlight, or indoors light, light sensitive devices may be used. Specifically, photovoltaic (PV) cells may be incorporated into the sensor nodes in order to capture and absorb photons that are emitted by light. Actually, PV cells contain semiconducting materials, such as silicon, which are able to convert the energy of light that is captured into a flow of electrons [27, 28];
    - Thermal-based energy harvesting is based on the generation of energy due to the existence of either heat or variations in temperature. The conversion of thermal energy to electric energy is achieved via either pyroelectric transducers or Thermo Electric Generators (TEGs). The former produce electricity from charge changes that are created on the surface of pyroelectric crystals due to temperature fluctuations, while TEGs take advantage of either Seebeck, or Joule, or Peltier, or Thomson effects [22, 23, 25];
    - Flow-based energy harvesting uses the transformation of the energy produced by wind and water into electric energy. Specifically, the energy harvesting via wind in WSNs is based on the use of propellers, triboelectric, and piezoelectric devices of small dimensions for the exploitation of rotations, and the vibrations caused by the flow of wind. The existence of moving or falling water near by the nodes is very useful. Specifically, small sized hydrogenerators, which convert mechanical energy created by water movement into electricity, are used. Additionally, the use of seawater batteries, consisting of electrodes, is another alternative for WSNs located in sea [22];
    - Biomass-based energy harvesting is performed by piezoelectric and triboelectric nanogenerators that scavenge energy from decomposable wastage, organic constituents, chemical substances, human urine, and other types of biological

material. In this way, WSNs can be powered in environmental, biomedical, and various other applications [22, 24].

- According to the specific type of the quantity that it is used, energy harvesting via external sources of energy can be further classified as: mechanical-based and human-based.
  - Mechanical-based energy harvesting is achieved by using the so called Mechanical-to-Electrical Energy Generators (MEEGs). Such devices include piezoelectric, electromagnetic, or electrostatic mechanisms in order to scavenge energy created by vibrations, stress-strain and pressure [22, 25].
  - Human-based energy harvesting is performed in Wireless Body Area Networks (WBANs) in which nodes are either deployed on human bodies or implanted in human bodies. In such networks of this type, human-based energy harvesting is ideal for energy supply. It refers to the scavenging of the energy created during various activities or processes of the human body, such as walking, finger movements, blood flow, and body heat. Electroactive materials, miniscule thermoelectric, piezoelectric, or triboelectric generators, and tiny rotary devices may be used for this purpose [23, 28, 29].

1.6.2.3 Wireless Energy Transfer

Wireless energy transfer (WET) is another method used to increase energy residues of the nodes in WSNs. Actually, this method, is described as the ability of wirelessly transferring electrical energy among nodes by using appropriate hardware components [8]. When exploiting this method, energy may be transferred from the segments of the network with higher energy levels to segments having lower amounts of energy residues so as to balance the energy levels of the network [30]. Power transfer in a WSN can be accomplished using either stationary sources or mobile chargers. Energy is provided to the nodes via charging vehicles and robots, or energy transmitters. Furthermore, sensor nodes are capable of transferring energy to their neighboring nodes [31]. Energy wireless transfer can be achieved in three ways:

- Inductive coupling: energy can be wirelessly transferred from a primary to a secondary coil that is placed at a close distance. The amount of generated energy is proportional to the size of the coil. This method is simple and safe to apply [8];
- Magnetic resonant coupling: power is transferred from a main coil (source) to a secondary (receiver). This can be accomplished through the utilization of resonant coils that have the same resonant frequency and are either loosely or strongly coupled [31]. Compared to inductive coupling, this method provides the power transfer over longer distances, and it is not a radiative method. So, it causes almost no harm to humans and does not have need of line of sight;
- Electromagnetic radiation: a source device transmits energy via electromagnetic waves through its antenna to another device’s receiving antenna. There are two types of electromagnetic radiation: omnidirectional and unidirectional. By using EM, energy can be transmitted over long distances [32].

1.7 Algorithm-Based Energy Sustainability in WSNs

Energy sustainability in WSNs can also be achieved by exploiting algorithm-based methods that are analyzed later on in this section. In order to support their comprehension, the theoretical background that concerns first the protocol stack of sensor nodes and base stations and next the communication technologies used in WSNs is examined.

1.7.1 Protocol Stack of Sensor Nodes and BSs

The operation of both every sensor node and the base station is managed by theso called protocol stack that, as illustrated in Figure 8, consists of five layers, i.e.: the application layer, the transport layer, the network layer, the data link layer, and the physicallayer [1, 3, 33].

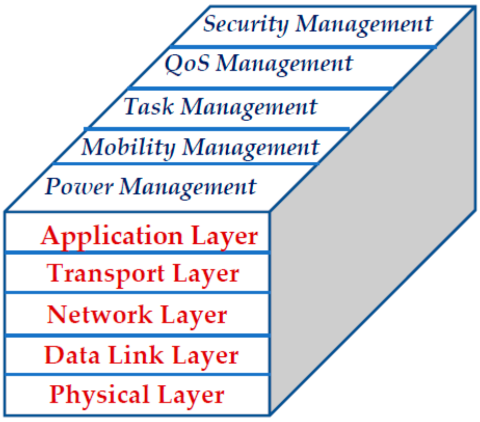

Figure 8: Protocol stack of a wireless node.

Each one of these layers is responsible for definite tasks [1] Specifically:

- Application layer establishes the interface between the end user and the application. According to the type of the application and its specific characteristics, this layer is able to modify its content using the most suited algorithm;
- Transport layer ensures the preservation of the data flow;
- Network layer is responsible for the routing of the transferred data from the transport layer to their destination;
- Data Link layer is responsible for multiplexing of data streams, error control, medium access control (MAC) and detection of data frames. In this particular layer, point-to-point,as well as point-to-multipoint connections within a network, become dependable;
- Physical layer is responsible for the selection of the communication frequency, the generation of the carrier frequency, the signal detection, the signal modulation, andthe data encryption.

In addition, the appropriate operation of WSNs depends on five management planes that namely are: power, mobility, task, QoS (Quality of Service), and security plane [33]. Specifically:

- The power plane preserves energy by managing the way power is consumed;
- The mobility plane ensures the retainment of data routes by monitoring and recording the nodes' movement;
- Sensing tasks in a specific area of the network are scheduled and assigned by the task management plane to only some of the nodes, enabling the rest of them to perform tasks, such as routing and data aggregation;
- Fault tolerance, error control and operation's optimization are handled by the QoS management plane, in accordance with specific QoS metrics;
- The monitoring, management and the control of network's security is regulated by the security plane;

1.7.2 Communication Technologies Used in WSNs

Modern scientific and technological progress enabled the development of advanced standards and technologies for wireless communications that aim to empower the exploitation of WSNs and Internet of Things (IoT) and support corresponding applications. Actually, there is not a specific technology developed that is able to be efficient when used in all kinds of wireless communications. Instead, there are numerous technologies with various characteristics that have been proposed. Therefore, it is very important to select the appropriate technology in order to suit best the requirements of particular types of applications [34].

For instance, the transmission range is a metric used in order to categorize such technologies as either short-range (with coverage 10 m), medium-range (with coverage 10-100 m), or long-range (with coverage 100 m). Bluetooth (in its classic version) and Radio Frequency Identification (RFID) are probably the most widely used examples of the first of these categories [35]. Likewise, Ultra-Wideband (UWB), Thread, Wi-Fi, ZigBee, along with two newer versions of Bluetooth, i.e., Bluetooth Smart (which is known also as Bluetooth Low Energy-BLE), and Bluetooth Long Range, are characteristic examples of are medium-distance wireless communication technologies [36]. Likewise, LTE-M, LoRa, NB- IoT and Sigfox are representative paradigms of LPWA (Low Power Wide Area) technologies, which is an emerging family of long-range wireless communication technologies [37-39].

In Table 1, some of the most important communications technologies that have been proposed for use in WSNs are enlisted along with some of their technical characteristics.

Communication Technology	Communication Standard	Maximum Transmission Range	Maximum Data Rate
Bluetooth	IEEE 802.15.1	10 m	~ 3 Mbps
RFID	ISO18000-6C	~ 0.1 m (LF) ~ 1 m (HF) ~ 12 m (UHF)	~ 100 Kbps
UWB	IEEE 802.15.4.z	25 m	~ 27 Mbps
Thread	IEEE 802.15.4	30 m	~ 250 Kbps
Wi-Fi	IEEE 802.11	~ 45 m (indoors) ~ 100 m (outdoors)	~ 2.4 Gbps
ZigBee	IEEE 802.15.4	~ 100 m	~ 250 Kbps
Bluetooth Smart (BLE)	IEEE 802.15.1	100 m	~ 1 Mbps
Bluetooth Long Range	IEEE 802.15.1	~ 1000 m	~ 2 Mbps
Z-Wave	Z-Wave standard	100 m-800 m ~ 1.6 km (Long Range)	~ 100 Kbps
LTE-M	3 GPP	~ 5 km	~ 1 Mbps
NB-IoT	3 GPP	~ 1 km (urban) ~ 10 km (rural)	~ 200 Kbps
LoRa	LoRaWAN	~ 5 km (urban) ~ 20 km (rural)	~ 50 Kbps
Sigfox	Sigfox	~ 10 km (urban) ~ 40 km (rural)	~ 100 bps

Table 1: The most popular communication technologies used in WSNs.

1.7.3 Algorithm-Based Methods for Energy Sustainability in WSNs

Energy sustainability of WSNs may be accomplished by using appropriate algorithm approaches depending on the type of the application. As illustrated in Figure 9, algorithm-based mechanisms may be classified into three main categories, i.e., data driven, duty cycling, and energy efficient routing, along with various subcategories [9, 10, 12, 40]. They are all described in what follows in the rest of this section.

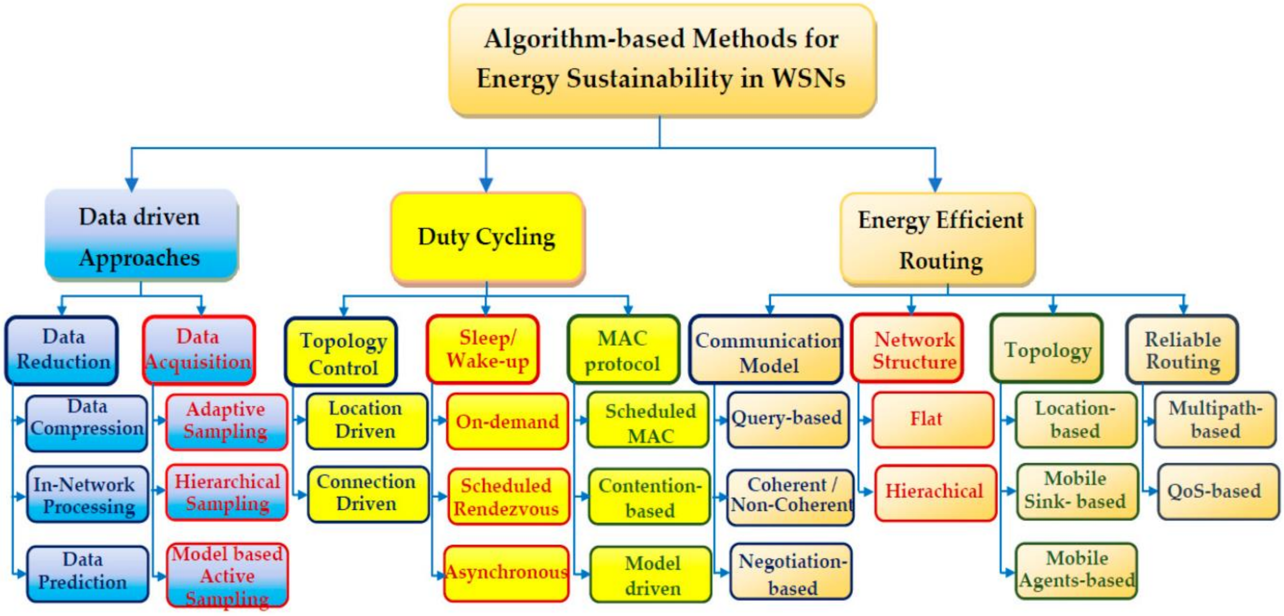

Figure 9: Categorization of algorithm-based methods for energy sustainability in WSNs.

1.7.3.1 Data Driven Methods

Data driven approaches aim to limit the amount of sampled data, while preserving the accuracy within acceptable limits, depending on the requirements of each application [41]. These approaches are distinguished into two types, data reduction and data acquisition approaches, and they are focused on the optimal management of the sensed data.

- Data reduction aims to minimize the amount of the data that need to be sensed and transmitted to the sink and consequently limit the number of transmissions required. This can happen by reducing the sampling frequency of the sensor nodes to avoid the creation of redundant samples, or by reducing the mandatory sensing tasks [10]. The methods used for data reduction are:
    - Data compression: by compressing the sensed data, the size of the aggregated data is reduced prior to their transmission to the BS. So, both the size of the transmitted packets and the transmission time are reduced and consequently energy is saved [10];
    - In-Network processing: is typically performed by intermediate nodes located among the data sources and the BS. Specifically, nodes along with executing their sensing tasks, they can also use their microprocessors in order to process the information data that they have gathered and then transmit only the really essential data packets to the BS. So, the in-network processing of the sensed data reduces the number of the data transmissions performed and consequently saves great amounts of energy [42];
    - Data prediction: prediction models are created in order to give answers to the queries generated by the BS. These answers can be either prediction values that are associated with statistical or empirical probabilities, or future metrics that are estimated-based on the prediction model. Perpetual monitoring of a FoI,

implies frequent alterations of the measured values. In data prediction approaches, the sensor nodes gather sample data within predefined periods of time and compare the actual data with the prediction values. Then, they transmit their data in case a deviation is noticed, thus decreasing the number of the unnecessary transmissions and subsequently the corresponding expenditure [12, 43].

- Data acquisition approaches intend to restrict the energy that is consumed during nodes' sensing tasks by using appropriate acquisition methods. Sensing is a power consuming process since power hungry sensors or A/D converters are exploited in many applications [44]. The data acquisition methods are:
  - In Adaptive sampling, in contrast with the traditional sampling methods where the rate is predefined, the number of samples captured by the nodes is adjusted- based on each application's needs. In this way, the energy dissipation is limited, and the battery life cycle of nodes is prolonged [45];
  - Hierarchical sampling is used in networks that are made of nodes that contain sensors of various types. Since every sensor is defined by distinctive characteristics, such as accuracy, resolution, and power consumption; this method dynamically decides which category of sensors to trigger. Typically, simple sensors are more energy efficient than advanced sensor nodes, but they lag behind in terms of their characteristics. Oppositely, sensors with a more complex design and way of operation, provide more precise information of the sensed data. Because of that, in hierarchical sampling approaches, low-power sensor nodes are used in order to monitor data regarding the FoI. Once an event is detected or a more thorough evaluation is required, advanced sensors take charge of the sensing process [46];
  - Model-based active sampling: in these methods, mathematical models are implemented, in order to limit the sampling rate and preserve the nodes energy levels. Specifically, these models use the sampled data and aim to predict the corresponding subsequent values within a confidence level, reducing the frequency of the sampling. In this category, each node locally computes a model-based on the data trend and creates the information that will be sent to the BS, instead of transmitting a number of raw samples to the BS. When there is no remarkable deviation between the sensed data and the model prediction, nodes do not have to communicate with the sink. When the sensed data differ from the model, nodes must update their model and accordingly report to the BS. Such models can be statistical, machine-learning, probabilistic etc. [26, 47].

1.7.3.2 Duty Cycling

Energy saving in a WSN can be accomplished through managing the activity status of the communication module of the nodes. Specifically, the transceiver of the node should be powered off when not receiving or transmitting data, and powered on once there are available data to be handled by the radio submodule. The process of switching the activity status of the transceiver among various modes (i.e., transmission-Tx, reception-Rx, idle, and sleep) depending on the current network requirements is known as duty cycling [48]. It is implemented by using appropriate wake-up oscillators that perform clock generation [49, 50] and wake-up receivers that perform the idle listening while keeping the main radio completely off [51-53]. Duty cycling schemes are categorized into three main classes: Topology control, sleep/wake-up mechanisms, and MAC protocol. Duty cycling approaches are implemented.

- Topology control protocols correlate with the redundancy of network. In some applications, nodes are randomly deployed, and additional nodes are used to confront likely to occur node failures. These protocols intend to dynamically adapt the network's Topology to each application's needs and seek for the minimum number of nodes that ensures the connectivity of the network by utilizing redundant nodes [8]. The nodes that have no crucial role in ensuring the coverage and the connectivity requirements, can temporarily fall into sleep mode in order to preserve their energy levels, and wake up once needed. Topology control protocols are distinguished in location driven and connectivity driven [12];
    - Location driven protocols determine the activity status of a node, i.e., whether and when this node should be activated or deactivated (sleep mode), by taking into consideration the exact location of this node and all of the rest network nodes (which is known);
    - Connectivity driven protocols ensure the preservation of connectivity by adaptively managing the activation or deactivation of the network nodes. Specifically, only the sensor nodes that are required to maintain the network connectivity remain active while all of the rest network nodes remain in sleep mode, thus saving energy.
- Sleep/Wake-up schemes aim to save energy reserves by lessening the periods that the radio submodule of nodes remains inactive, since even when inactive they still consume energy. There are three types of such protocols, which are differentiated regarding transmission and reception patterns. They are: on-demand, scheduled rendezvous and asynchronous [12].
    - In On-Demand mechanisms nodes should be awake only when it is necessary to communicate with other nodes. Informing a sleeping node that an adjacent one is trying to reach it so as to initiate communication, can be achieved by utilizing multiple radios with different operational characteristics (i.e., rate and power). On-demand mechanisms are ideal for applications that are defined by a low duty-cycle, such as the detection of a special event (i.e., fire), since, in such cases the sensor nodes monitor the environment and wake up as soon as they detect an event. So, nodes remain active only when needed [8]. Yet, utilizing on-demand mechanisms, usually requires the presence of two different channels, one that is used for the normal data communication and one that is responsible for waking up the nodes when required [12];

- Scheduled rendezvous methods determine a wake-up schedule that is the same for all the nodes of a WSN. Nodes simultaneously wake up and once they are awake, they remain so for a definite period of time and go back to sleep all together until their next rendezvous. In order to ensure simultaneous wake-up, nodes must be synchronized. Additionally, to maintain the same wake-up schedule, nodes use deterministic, random or specific wakeup patterns [9];
- In asynchronous duty cycling mechanisms, each node selects when to either wake up or sleep, regardless of the activity status of its neighbors. To do this, the existence of overlapping periods between the wake-up periods of the nodes is compulsory. In order to discover the transmission of asynchronous senders, the sender transmits either a stream of periodic discovery messages or a single long discovery message. In each case, the duration of listening time has to be adequately adapted to transmission time [9, 12].

- Medium Access Control-MAC layer is a sublayer within the Data Link layer that constitutes the link between the Physical and the Network layer and is responsible for the data transmission between the nodes [54, 55]. To communicate with each other, sensor nodes utilize a shared medium. In the case of WSNs, the medium is the radio channel [56, 57]. The decision regarding the competing nodes that will eventually access the shared medium is handled by MAC protocols that also focus on how to avoid collision during the transmission [58 ,59].

In WSNs, designing energy efficient MAC protocols is a challenging task and constitutes one of the major characteristics that defines whether the protocol is well designed or not [60, 61]. MAC protocols are classified in three main categories: scheduled, contention-based and hybrid [56].

- In scheduled MAC protocols, nodes can access the shared medium channel utilizing a source which depends on the used protocol. There are three basic types of scheduled MAC protocols: TDMA, FDMA and CDMA.

In TDMA-Time Division Multiple Access protocols, time splits into timeframes and each of them is composed by a specific number of equally sized slots, called time slots. One or more time slots of a timeframe are given to each node allowing it to transmit or receive data only through them. Upon agreement between the nodes and based on the schedules of their adjacent ones, which are handled by the BS, the nodes select their individual time slots on which data can be transmitted or received. Thus, a node can remain in sleep mode and activate its transceiver only when its time slot is reached, resulting in energy saving [12].

Regarding FDMA-Frequency Division Multiple Access and CDMA-Code Division Multiple Access MAC protocols, the medium can be accessed using a frequency band or a specific code, respectively. TDMA-based are the mainly used MAC protocols in WSNs, since the implementation of FDMA requires nodes that are equipped with high-priced transceivers, and CDMA demands higher levels of computational power that leads to energy depletion [57].

- The main objective of the contention-based MAC protocols is the channel collision avoidance that influences the wake-up/sleep time of the nodes. Actually, it is very often for the nodes of a WSN to have to wait for a non-specific period of time in order to access the medium, due to heavy traffic and collision in it. This happens because nodes try to send their packets though the medium but with no success since it is busy, and thus they have to wait until the load in it is decreased. The nodes resend their data and in case the load remains the same, they will have to wait to resend them. This implies longer periods of nodes' inactivity, leading to the exhaustion of the batteries. Collision avoidance can be achieved utilizing an algorithm called Carrier Sense Multiple Access with Collision Avoidance-CSMA/CA [57]. Several protocols have been developed allowing nodes to enter sleep state and wake up at certain periods of time in order to check the availability of the channel, so as to send their data whenever possible and prevent energy waste;
- Hybrid protocols combine features and methods used by both scheduled and contention-based MAC protocols, in a way that improves the nodes' performance in cases of increased traffic load [56, 57].

1.7.3.3 Energy Efficient Routing

By default, the transmission and routing of data in WSNs consume great amounts of the energy that sensor nodes retain [62]. Therefore, in order to preserve the lifetime of nodes and consequently of WSNs, it is critical to implement routing protocols that are energy efficient.

The energy efficient routing protocols are generally classified, in terms of their organizational or functioning characteristics, into four main categories that namely are: Communication Model, Network Structure, Topology, and Reliable Routing [40, 63].

- The protocols belonging to the Communication Model category typically can deliver more data for a certain amount of energy. Nevertheless, the delivery of data is not assured. They are classified as Query-based, Coherent/Non-Coherent, and Negotiation based.
    - Query-based protocols use enquiries to support the transfer of data from nodes that own information to nodes that request specific pieces of this information. Protocols of this type enable both multiple path routing and dynamic network topologies [40];
    - Coherent protocols perform minimum processing of the sensed data and then they send these data to other nodes, called aggregators, which further process them. In Non-Coherent routing protocols, nodes process sensed data locally before they transmit them [63];
    - Negotiation-based protocols use meta-data negotiation patterns in order to reduce the quantity of redundant data at destination network nodes. In this way, energy efficiency is achieved.
- Energy efficient routing protocols of Network Structure category are classified as either Flat or Hierarchical.

  - In Flat protocols there is not any hierarchy adopted and every sensor node has the same role as all of the rest network nodes. Protocols of this kind perform well in networks constituted from a small quantity of sensor nodes [40];
  - In Hierarchical protocols, the role of each one of all network nodes depends on the position that it holds within the overall hierarchical structure of the sensor network [64]. In this way, data aggregation is enabled, and great scalability is achieved. Additionally, load balancing is achieved [65].
- Energy efficient routing protocols belonging to the Topology category use position related information in order to route data. They are further classified into three subcategories, namely: Location-based, Mobile Sink-based, and Mobile Agents-based.
  - In Location-based protocols, all nodes know not only their own location but also the positions of both their neighboring nodes and the destination nodes during data routing. Consequently, the most energy efficient routing paths are followed [63];
  - Mobile agents-based routing protocols presume that a movable entity collects the sensed data from the individual network nodes in order to convey these data to the BS. The arrival of mobile agents near the network nodes that sense data reduces the energy expenditure for data transmission of these sensor nodes. Additionally, the traffic load in the entire network is reduced [40];
  - Mobile sink-based protocols suppose the existence of one or more sinks (i.e., base stations) that move around the FoI in order to collect data sensed by the network nodes. In this way, the energy consumed by the network nodes in order to transmit data is considerably reduced [40].
- Reliable Routing protocols pursue the attainment of increased trustworthiness in data routing either by satisfying specific QoS metrics or by using a number of alternative paths in order to route data. They are categorized into two corresponding subcategories, i.e., QoS-based protocols and Multipath-based protocols depending on whether they chase QoS metrics or implement data routing via multiple paths.
  - QoS-based protocols consider not only energy consumption, but also other metrics such as end to end delay and quality characteristics of the data transmitted. Protocols of this kind achieve routing with enhanced fidelity [63];
  - Multipath-based protocols route data from nodes to sinks via various paths, in order to perform load balancing, overcome node failures and congested paths, and decrease end-to-end delay [40].

CHAPTER 2:
Challenges of Energy Saving Methods

In the previous chapter the various hardware-based and algorithm-based methods that have been proposed in order to support the energy sustainability of Wireless Sensor Networks were analytically presented. Despite the benefits that these methods provide, there are certain weaknesses, disadvantages and problems that are incorporated into these mechanisms too, which obstruct their successful deployment and thus pose corresponding challenges and trigger issues of future research.

2.1 Challenges in Hardware-Based Methods

Regarding the submodules of sensor nodes, as aforementioned, the use of low-power electronic components is necessitated [8, 10, 12]. However, the components having the highest energy efficiency do not necessarily achieve the best performance standards. That is why the specifications and selection of the hardware components should be meticulously studied before being adjusted to the sensor nodes. In addition, Power Optimization through the appropriate switch among active, idle, and sleep modes of operation cannot be used in applications in which continuous operation of nodes is necessitated [8, 12]. Moreover, Passive Sensors cannot be used in all types of applications [16]. The method of Dynamic Voltage Scaling that is applied in the processing unit of nodes, is effective only when sensing requests are less frequent [17, 18]. The usage of Cognitive Radio method in order to achieve the dynamic selection of the most suitable radio channel, inevitably requires the existence of multiple radio channels, thus increasing complexity and cost [10]. The increase of latency and the modification of routing paths are the main weaknesses of Adaptive Power Transmission [8, 13]. In many cases, the use of Directional Antennas is not feasible if localization methods are not applied in order to assist orientation procedures [10]. Likewise, the utilization of Short Communication Links requires the existence of many adjacently positioned nodes. For this reason, this methodology is not applicable in WSNs having sparse distribution of nodes [10]. Regarding Rechargeable Batteries, the recharge of all batteries of the nodes in a network may be a complicated or even impossible task to perform, depending on the deployment of the nodes. Additionally, besides their limited capacity, rechargeable batteries not only are unable to remain fully charged for long time, but they also are characterized by a limited number of recharge cycles [8, 11]. Of course, modern 3D-printed Lithium-Ion microbatteries have enhanced capabilities. Yet, further research regarding alternative materials, manufacture techniques and designs of microbatteries is needed [66-70]. Supercapacitors have certain advantages over batteries. Yet, not only they are costly, but they also have low energy density and high rate of self-discharge [71-74]. Hybrid Ion Capacitors (HICs) (known also as supecapatteries) that consist of one battery-type electrode and a capacitor-type electrode seem to be a very promising alternative that achieves higher power capacity, power density, energy density, and efficiency [75-79].

Energy Harvesting, as aforementioned, can substantially upgrade the energy sustainability in WSNs [22]. Thus, novel research is necessitated not only for the development of advanced equipment such as low energy harvesters, converters, and energy storage systems (ESS) [80-87], but also in order to handle certain issues such as the high cost of implementation, the low power generated, and the presence of fluctuations and instabilities [88, 89]. Furthermore, health limitations associated with RF power obstruct the wide use of RF-based energy harvesting. Moreover, ambient RF is neither predictable nor controllable [24]. In light-based energy harvesting, the amount of the gathered energy is determined by the intensity of ambient light. Yet, although the availability of light is absolutely controllable in indoor applications, in outdoor applications is existing only during daytime as long as the weather conditions are adequately good [27, 28]. Thermal-based energy harvesting not only is unpredictable and uncontrollable when caused by temperature variations but also has low efficiency [25]. Flow-based energy harvesting is not only unpredictable but also uncontrollable [24]. Biomass-based energy harvesting, due to its nature, is feasible only in a specific type of applications. Mechanical-based energy harvesting is unpredictable. Similarly, human-based energy harvesting due to human activity is unpredictable, while due to physiological procedures is both unpredictable and uncontrollable [22].

Likewise, wireless energy transfer is associated with various weaknesses. Specifically, energy transfer requires corresponding cross-layer provision covering the MAC, link, and application layers. The achievement of energy transfer requires the use of specialized equipment thus growing the employment cost [8]. Moreover, in the case that robotic vehicles or other types of mobile nodes are used to charge network nodes special algorithms for their navigation are required. Additionally, by using Inductive Coupling for wireless energy transfer only short transmission distances can be covered [30]. The efficacy achieved is decreased by any misalignment existing between the transmitter coil and the receiver coil. Special actions must be taken to avoid the presence of mutual coupling effect that is the cause of interference among nodes. Wireless energy transfer via Magnetic Resonant Coupling requires not only the attainment of alignment between the coils of the transmitter and the receiver, but also the adjustment of resonant frequency in various nodes [31]. In wireless energy transfer via Electromagnetic Radiation, line of sight is essential, and the presence of radiation triggers various health and safety concerns [32]. In order to provide a synoptic overview of the aforementioned statements, the basic operation along with the main strengths and weaknesses of each one of the hardware-based methods for energy sustainability in WSNs are presented in Table 2.

Low power electronic units	Use of low-power sensors, processors, and transceivers	Energy efficiency and low power consumption.	Increased cost of application
Power optimization	Use of active, idle and sleep operation modes of hardware.	Energy saving when nonstop nodes' operation is not needed	Not applicable where continuous measurements are required.
Use of Passive Sensors	Sensors containing no active circuits are used.	Practically no energy dissipation takes place.	They cannot be used in all kinds of applications.
Dynamic Voltage Scaling	Frequency and voltage in line with the processing tasks.	This technique increases energy efficiency of the processing unit.	It is effective only when sensing requests are less frequent.
Cognitive Radio	Communication needs define radio channel selection.	High power channels are not used for wakeup-call communication.	The existence of multiple radio channels adds complexity and cost.
Adaptive Transmission Power Control	Power in line with the distance and energy residues of nodes.	Energy spent for transmission is in line with existing conditions.	Delay is increased. Routing paths are modified.
Directional Antennas	Signals are received and sent in one direction at a time.	Increase of throughput, decrease of power needed and overhearing	Localization methods may be needed for orientation purposes.
Short Communication Links	Communication is made by using many transmissions over short distances.	Less energy consumption during transmission.	More nearby allocated nodes are needed to be deployed. Not applicable in sparse networks
Rechargeable Batteries	Batteries that can be recharged many times are used.	High energy density. Low cost. Low rate of self-discharge.	Long charging time. Short recharge cycle life. Limited lifetime.
Supercapacitors	Capacitors of high capacitance are used.	Short charging time, long recharge life cycle and lifetime.	Expensive. High rate of self -discharge. Low energy density.
RF-based Energy Harvesting	DC electricity is made from Ambient/dedicated wireless signals carrying RF waves.	Dedicated RF is at least partially predictable and partially controllable.	There are health limitations for RF power. Ambient RF is neither predictable nor controllable.
Light-based Energy Harvesting	Electricity created by photons emitted by light (solar/indoor)	Solar-based is predictable. Indoor is predictable and controllable.	Solar is uncontrollable; available only in daytime if weather is good.
Thermal-based Energy Harvesting	Energy is generated due to the existence of either heat or variations in temperature	This method is controllable when caused by heat.	It is unpredictable and has low efficiency. It is uncontrollable when caused by temperature variations.
Flow-based Energy Harvesting	Energy produced by wind and water is scavenged.	This type of energy harvesting is environmentally friendly.	It is neither predictable nor controllable.
Biomass-based Energy Harvesting	Energy is made from various types of biological material	It is an inexpensive method with high efficiency.	It can be used in specific types of applications.
Mechanical-based Energy Harvesting	Energy scavenged from strain, vibrations, and pressure.	This type of energy harvesting is controllable.	It is unpredictable.
Human-based Energy Harvesting	Energy harvested from human activity or physiological tasks.	Human activity-based energy harvesting is controllable.	Physiological: unpredictable, un-controllable. Activity: unpredictable
WET: Inductive Coupling	Energy transferred from a primary to a secondary coil.	Simple and safe to apply. High efficiency in small distances.	Loss of power. Inefficient for long distances. Non-directionality.
WET: Magnetic Resonant Coupling	Energy transferred between coupled resonant coils	Non-radiative. No need of line of sight. Long distances covered	Need for alignment between coils and resonant frequency tuning.
WET: EM Radiation	Energy transferred via electromagnetic waves.	Energy transfer over long distances is achievable.	Life of sight is needed. Radiation emitted is harmful.

Table 2: Synoptic overview of the hardware-based methods for energy sustainability.

2.2 Challenges in Algorithm-Based Methods

First of all when selecting the communication technology to use in a WSN there are many specifications, other than energy efficiency, such as throughput, security, accuracy, robustness, and scalability, to consider [90-95].

Regarding data-driven approaches, as aforementioned, they are classified as data reduction and data acquisition approaches. In Data Reduction the suitability of Data Compression relies on the assumption that the energy needed to compress the data is less than that needed to transmit the raw (uncompressed) data while the accuracy of measurements is preserved. Additionally, this method may degrade QoS (i.e., accuracy, latency, fault tolerance and security) while trying to increase the network lifespan [10]. In-Network Processing is associated with non-negligible energy consumption [36]. Similarly, due to the fact that high computational power is required to create a prediction model, Data Prediction is suitable for networks where powerful sensor nodes with high-capacity batteries are exploited [12, 43]. Regarding Data Acquisition methods, Adaptive Sampling is characterized by high complexity and high computational overhead, thus necessitating central control [45]. Hierarchical Sampling sacrifices accuracy to achieve energy efficiency because simple sensors with low accuracy are mostly used while powerful sensors are used only when an event is detected and enhanced data are needed [46]. In Model-based Active Sampling mechanisms complex computations are needed, thus increasing processing load [47].

In Duty Cycling methods, the use of specialized modules is necessary [96-99]. In duty cycling via Topology Control methods, both location driven, and connectivity driven mechanisms take the knowledge of the positions of all network nodes as granted. Yet, this is not a trivial condition to fulfill. Additionally, if GPS modules are used to overcome this problem, such modules not only are costly but also cause interference to network communications [8, 12]. In relation to Sleep/Wakeup mechanisms, On-Demand methods require the existence of an additional radio for wakeup signaling, while in Scheduled Rendezvous clock synchronization problems occur, and in Asynchronous Schemes robustness trades off for energy consumption while latency is high [9, 12]. Regarding MAC protocol mechanisms, scheduled MAC methods are costly to implement. In addition, there are various weaknesses such as the hidden terminal problem (in CSMA) and the clock synchronization problem (in TDMA) [56]. Contention-based MAC protocols, suffer from high latency in packet delivery while in hybrid MAC protocols complexity increases accordingly to the number of network nodes [57]. Thus, novel research mut be carried out [100, 101].

Finally, as already mentioned, Energy Efficient Protocols may be classified according to Communication Model, Network Structure, Topology, and Reliable Routing [40, 63]. Regarding the first of these categories, Query-based protocols are not suitable for continuous data delivery, while Coherent/Non-Coherent protocols are related with low scalability, high overhead, and high end-to-end delay, and Negotiation-based protocols do not guarantee data delivery [40]. In the Network Structure category, Flat protocols have low scalability while Hierarchical protocols suffer from high overhead and high complexity and do not guarantee optimal routing [40]. In Topology category, Location-based protocols have high overhead and low scalability and require the use of GPS modules that are costly and interfere with network communications [63]. Mobile Agents-based protocols have low scalability, high latency, and high complexity, while Mobile Sink-based protocols suffer from delays on data delivery in routing paths and topology. In Reliable Routing category, both QoS-based protocols, and Multipath-based protocols suffer from high processing load [40].

In order to provide a synoptic overview of the aforementioned statements, the basic operation along with the main advantages and disadvantages of each one of the algorithm-based methods for energy sustainability in WSNs are presented in Table 3.

Data Compression	Nodes compress data prior to their transmission to the BS.	Reduction of size of transmitted packets and transmission time.	QoS reduction (accuracy, latency, fault tolerance security).
In-Network Processing	Nodes process data, prior to their transmission to the BS.	Data aggregation is performed. Reduction of data transmission.	Data processing may cause non-negligible energy consumption.
Data Prediction	Prediction models are created to restrict continuous sensing.	Data are transmitted only when they differ from predicted ones.	High level computations consume energy. Powerful nodes areneeded.
Adaptive Sampling	Adjustment of sampling rate in line with application needs.	Energy is saved, when applied in centralized implementations.	High complexity and overhead are caused. Central control is needed.
Hierarchical Sampling	Dynamically deciding which sensors must be activated.	Energy hungry sensors actuated only when high detail is needed.	Accuracy may be sacrificed to achieve energy saving.
Model-based Active Sampling	Models predict data to save energy in data acquisition.	The number of data samples are reduced via mathematical models	Complex computations are needed.
Location Driven	Nodes are activated according to their location.	Unnecessary activation of nodes is avoided.	Location must be known. GPS units are costly and cause interference.
Connectivity Driven	Nodes are activated to ensure connectivity and coverage.	Only necessary for connectivity and coverage nodes are active	Location must be known. GPS units are costly and cause interference.
On-Demand	Nodes awakened only when necessary to communicate.	Convenient for deployments with very low duty cycle.	An additional radio for wakeup signaling is needed.
Scheduled rendezvous	A mutual wake up schedule exists for all network nodes.	When a node is awake, nearby nodes are also awake.	Problems in clock synchronization obstruct the overall operation.
Asynchronous	Nodes are independent but have common active periods.	Simple implementation.	Robustness trades off for energy consumption. Latency.
Scheduled MAC	Nodes can access the shared medium channel.	The multiple access of network nodes is regulated.	Costly. Hidden terminal (CSMA). Clock synchronization (TDMA)
Contention based MAC	Protocols that aim at the avoidance of collision.	Robustness. Scalability. Idle listening reduction.	Increment of packet delivery latency.
Hybrid MAC	Scheduled and contention-based MAC features combined.	The flaws of scheduled and contention-based MAC amended.	Complexity increases accordingly to the number of nodes.
Query-based protocols	Enquiries are used to support the transfer of data.	Dynamic network topologies and multiple path routing are enabled.	Not suitable for continuous data delivery.
Coherent /Non-Coherent-based	Local processing: full in Non-Coherent least in Coherent.	Data transmissions are reduced.	High overhead, high end-to-end delay, low scalability.
Negotiation-based	Meta-data negotiation is used.	Redundant data are reduced.	Data delivery is not guaranteed.
Flat Protocols	All nodes have equal roles.	Ideal for small scale applications.	Remarkably low scalability
Hierarchical protocols	Nodes have roles according to network hierarchy.	Data aggregation. Great scalability.	High overhead. High complexity. Optimal routes not guaranteed.
Location-based protocols	Every node knows the location of all other nodes.	The most energy efficient routesare used. Latency is reduced.	High overhead. Limited scalability. GPS units are costlyand interfere.
Mobile agents- based protocols	A movable entity collects the data from nodes to the BS.	Energy expenditure for data transmission is reduced.	Low scalability. High latency. High Complexity.
Mobile sink- based protocols	Sinks move and collect data from the nodes.	Energy saving and reliability in increased. Connectivity enhanced.	Delays on data delivery. Routing paths and topology changes occur.
QoS-based protocols	Routing is performed based on various quality metrics.	High quality and fidelity in data transmission are achieved.	High processing overhead is caused.
Multipath-based protocols	Data from nodes are routed to sinks via various paths.	Load balancing done. Failed nodes and congested paths are overcome.	Processing load is considerably increased.

Table 3: Synoptic overview of the algorithm-based methods for energy sustainability.

CHAPTER 3:
Energy Efficient Routing Protocol LEACH and its Successors

3.1 Energy consumption aware protocol LEACH

Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the initially constructed hierarchical clustering protocols. LEACH is developed based on the assumption that the energy levels of all sensor nodes within a network are equal, although this is not realistic [102]. In this protocol, the Field of Interest (FoI) is divided into clusters of nodes on which some of the nodes are used as cluster heads (CHs). Their task is to aggregate the sensed data from vicinal nodes and then to transfer the collected data to the BS. Since data transferring is directly related to nodes' energy waste, cluster heads rotate randomly in order to balance nodes' energy levels and the network's lifetime accordingly.

3.2 Operation and architecture of LEACH protocol

The operation of LEACH protocol is separated into two phased rounds, the set-up phase (state) and the steady phase. Each round starts with the setup phase during which the clusters are organized, and the nodes are distinguished in non-cluster heads and cluster heads. As soon as the clusters are formed, steady phase is initiated, and data are transferred from the nodes to the cluster heads and accordingly to the base station.

The *setup phase* is comprised of three stages: the node's role selection, the clusters formation, and the scheduling. The selection of the cluster heads is based on probabilities. Once a node becomes a cluster head, it cannot be elected again, for P rounds. Hence, the probability of a node becoming cluster head again is $1/P$ [102]. A node n, chooses a random value between 0 and 1, and in case this arithmetic value is less than a threshold T the node becomes cluster head for the current round. The threshold is calculated accordingly to equation (1)

$$T(n) = \begin{cases} \frac{P}{1-P*(r \bmod \frac{1}{P})} & \text{, for } n \in G \\ 0 & \end{cases} \qquad (1)$$

where P is considered to be the desired cluster head percentage, r stands for the current round and G represents the group of nodes that have not been declared as cluster heads in $1/P$ rounds.

The elected cluster heads send a broadcast advertisement message (ADV) utilizing a non-persistent CSMA MAC protocol to the rest of the network's nodes to declare that they are the current cluster heads [103]. Upon the message's reception, the non-cluster head nodes choose which cluster they will join according to the intensity of the broadcast signal they receive. Each one of the non-cluster head nodes transmits a join-request message to the cluster heads of choice to inform them that will join their cluster. Afterwards, the cluster heads construct a TDMA schedule which they transmit to the nodes belonging to their cluster and once all nodes are aware of the schedule the steady phase begins.

The *steady phase* unfolds in frames and the nodes forward their sensed data to their cluster heads during their allocated time slot. Upon data reception from its cluster's nodes, each CH proceeds to data aggregation and further processing in order to improve quality of the received signals and restrict the noise. Subsequently, the processed data are forwarded to the BS.

Except for the assumption that nodes have equal initial energy, it is highlighted that LEACH protocol is also based on the assumption that the sensor nodes transmit data to the sink during their allocated TDMA slot. Moreover, it is assumed that all sensor nodes are located within communication range with each other and the base station [104].

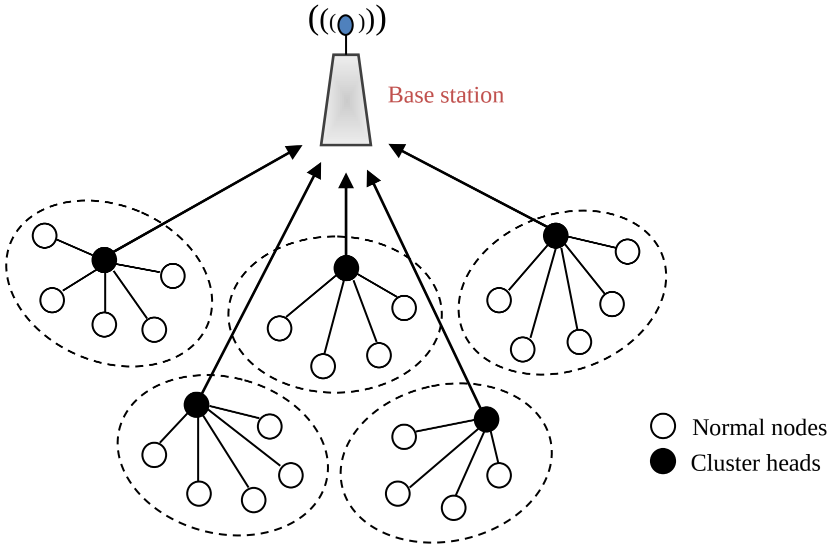

Figure 10: Architecture of LEACH protocol.

3.3 Disadvantages of LEACH protocol

Despite the contribution of LEACH protocol in WSN's energy saving, significant limitations arise:

- Cluster head nodes are the only ones responsible for directly sending the data to the base station. Hence, the failure of a CH decreases the robustness of the network.
- LEACH protocol utilizes single-hop routing, which in large networks consumes high levels of energy during the direct data transmission from the cluster heads to the base station.
- The usage of dynamic clustering entails extra overhead that could raise energy consumption.
- Cluster heads election is random and the nodes' power levels are not considered.

3.4 Successors of LEACH protocol

Despite being around for two decades, LEACH protocol still attracts the interest of many researchers engaging with WSNs. As a result, several modifications and optimizations of LEACH protocol have come up. Some of the successors utilize the single-hop routing or the multi-hop technique, while others combine both techniques. Some of LEACH's successors are briefly presented below.

In *LEACH-B (Balanced LEACH)* a balanced formation of clusters is achieved, by taking into consideration the desired proportion of CHs and the remainder energy of the sensor nodes. In this protocol, the number of CHs is defined by a fixed number *N*P*, where *N* is the number of nodes and *P* is the percentage of CHs. The election of the first CHs occurs randomly following the same process as in LEACH protocol. Upon their election, each CH transmits a broadcast message, which includes its status and its energy levels, to each node. In case the amount of the selected CHs is lower than N*P, some nodes with less time interval are chosen as CHs into a CH set and they announce their CH status to the network via a broadcast message. The calculation of the time interval is obtained according to the equation $t=K/E$, where K is a constant and E constitutes the energy of a sensor node. On the contrary if the number of the randomly selected CHs is greater than N*P, some CHs with lower residual energy are excluded to preserve the number of CHs as equal to the N*P. Although LEACH-B enhances the energy-load balance issue of the cluster and achieves better energy management compared to LEACH, it lacks in scalability and is characterized by complexity [105].

In *LEACH-C (Centralized LEACH)* the clusters formation is achieved by utilizing a central control algorithm. The steady phase is identical as in LEACH, while the setup phase differs, since the CHs are selected by the BS. More specifically, all nodes transmit their current location and their energy levels to the BS which processes the received information based on its global knowledge about nodes' locations, in order to form better clusters that demand less energy during transmission. The election is based on the nodes average energy, which is computed by the BS, and once a node's remaining energy is less than the average energy, it cannot be elected as a CH for the specific round. Upon clusters formation and CHs selection, the BS broadcasts a message which encloses information regarding the CHs ID. The current protocol achieves better cluster formation than LEACH but requires the existence of a positioning system adjusted to each node. Despite its improved energy efficiency in comparison to LEACH protocol, LEACH-C is associated with the problem of the early death of CHs with low energy, since in each round, there is a possibility of selecting nodes with less energy as CHs, instead of nodes with higher energy reserves [104].

LEACH-CE (LEACH Centralized Efficient) eliminates the issue of early death nodes that occurs in LEACH-C protocol, by selecting the nodes with higher energy levels as CHs in each round. During the first round, the BS chooses the CHs following the same process as in LEACH-C and once the clustering is completed, the CH node with the highest energy among the CHs, is defined as the final CH by the BS. Accordingly, the BS transmits a broadcast message with information related with the clusters to the network [106].

In *LEACH-D*, the selection of the CHs occurs based on a threshold value which is estimated considering the density distribution and the remaining energy of each node. Hence, the nodes located in high density and with high energy levels are chosen as CHs. In the next step, each cluster head defines its cluster's radius depending on its distance from the BS and the degree of connectivity. Proportionally, the sensor nodes adapt to their CH based on the distance between the CH and the BS and the energy reserves of the CH and the clusters are formed. In this protocol, the sensed data are transferred from the CHs to the BS exploiting mutli-hop transmission [107].

In *LEACH-L*, the CHs that are located far away from the BS choose CHs that are closer to the BS as a relay node, based on the energy levels of the relay node and its distance from the BS, while CHs that are close to the BS transmit their data directly. Although LEACH-L protocol prolongs the lifetime of large scale WSNs where the BS is located distantly from the network, the requirement of nodes' location knowledge raises the total cost and increases the complexity [108].

In *TL-LEACH (Two Levels LEACH)* the clusters and the cluster head nodes are categorized in two different hierarchies/levels. Upper-level CHs are characterized as primary and lower-level as secondary. Lower-level CHs aggregate the sensed data from their cluster's nodes, perform partial local processing and transmit the resultant data to the primary CHs. Then, primary CHs proceed to complete local processing and transfer the data straight to the BS. By utilizing a two-level clustering more nodes exploit short distances and fewer nodes use longer distances in order to transmit their data to the sink, leading to an increment of network's lifespan. Due to the fact that the primary nodes are close to the BS, they are facing the so-called hotspot issue, which means that they tend to deplete their energy faster than the CHs in the lower level [109].

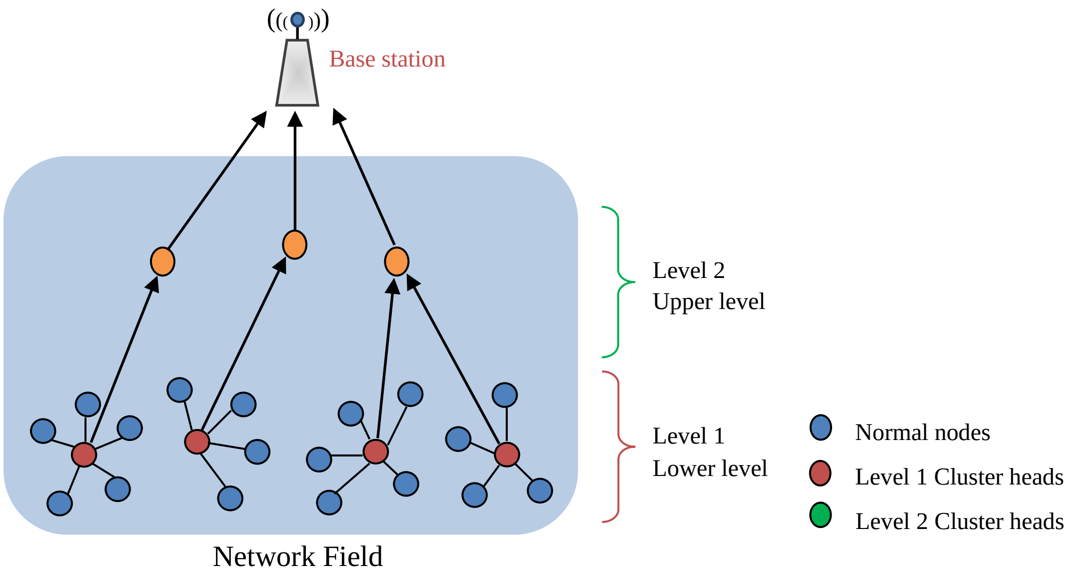

Figure 11: Topology of TL-LEACH protocol.

I-LEACH protocol performs two substantial functions: the detection of "twin nodes" and the determination of sub-cluster heads. In networks where nodes are randomly deployed, some of them may be located close to each other meaning that they can sense the same data. Such nodes are known as twin nodes. Since the same data can be acquired by one of them, it is important to keep the twin node in sleep mode until the energy of the other is consumed. In I-LEACH, CHs are equally distributed in the network's area and sub-cluster heads are utilized to prolong WSN's lifespan [110].

In *O-LEACH (Orphan LEACH),* the nodes that do not belong to any CH are counted as orphan nodes. This protocol has two different schemes. In the first scheme, a node that belongs to a cluster operates as a gateway for the network's orphan nodes. Orphan nodes transmit their sensed data to the node-gateway which aggregates and forwards them to the BS utilizing single-hop communication. In the second scheme, sensor nodes lying in an uncovered area of the network compose a sub-cluster and choose a CH. The selection of the CH is based on the shortest distance from the gateways. The orphan node that lies closer to the gateway will be the CH. O-LEACH achieves better scalability, energy saving, connectivity rate and coverage compared to LEACH protocol [111].

In single-hop clustering, CHs transfer their data directly to the sink. As a result, sensor nodes located far from the BS drain their energy faster than nodes located closer to the BS, since energy consumption is proportional to the distance. *U-LEACH (Unequal Clustering LEACH)* protocol aims to reduce the hotspot issue that nodes close to the BS face. This protocol utilizes an unequal clustering technique, where concentric cycles with diverse sizes are considered as clusters. The size of the clusters depends on their distance from the BS thus, the further the cluster is, the smaller its size [112].

V-LEACH (Vice LEACH) protocol handles the issue of early dead cluster heads that may occur in LEACH, where nodes' energy reserves are not considered during CHs' selection. In V-LEACH except for the CHs and the normal nodes, each cluster includes an extra type of nodes that are called vice cluster heads. Vice cluster heads undertake CHs' role as soon as they run out of energy. The process followed for CHs election is the same as in LEACH protocol and in each cluster, the sensor node with the highest energy reserves turns into a vice cluster head. Although this protocol enhances the data delivery success rate, it is inferior in scalability [110, 113].

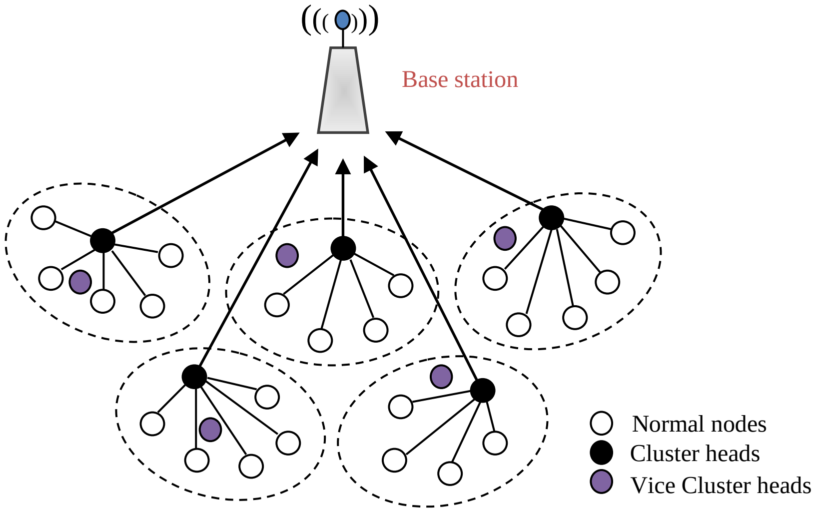

Figure 12: Topology of V-LEACH protocol.

DL-LEACH (Dual-hop Layered LEACH) exploits a dual-hop communication method, that combines both single-hop and multi-hop transmissions. Precisely, the network is divided into layers. The layer which is closer to the BS is considered as the lower level and accordingly the sensor nodes that are located closer to the BS belong to this level. The election of CHs is done in a similar way to LEACH protocol. Upon data aggregation, CHs seek for others belonging to a lower level to forward their data. Likewise, the lower-level CH will accumulate its clusters' data and will transmit its data and those received by the upper-level CH, to a CH in a lower level. In case there is no lower level, the CH will forward the data to the BS. Additionally, in order to transmit their data, lower-level nodes calculate their distance from their closer CH and the BS and if the BS is closer than the CH, they transmit their data directly to the BS. If not, data are forwarded via the cluster heads of upper layers. Even though DL-LEACH leads to great energy saving, the lifetime of the sensor nodes in large scale deployments is limited [114].

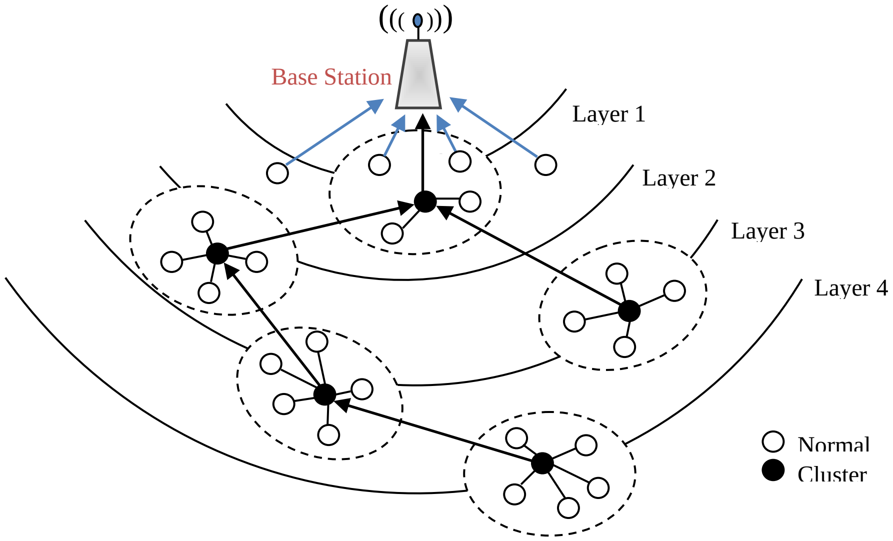

Figure 13: Topology of DL-LEACH protocol.

In *MR-LEACH (Multi-hop routing LEACH)* the FoI is separated into diverse layers. Each layer has its own clusters and the CHs of each layer cooperate with those of their adjoining layer. The size of the clusters is the same in all layers. The aggregated data from the more distant clusters end up in the BS through multi-hop paths using the CHs of layers that are closer to the sink. Cluster heads are chosen based on their residual energy and the nodes choose their CH based on the strength of the received signal. The base station allocates a time slot for every CH, and each CH sets its own schedule to its cluster members [115].

While in most successors of LEACH CHs rotate during each round leading to a significant energy reduction, in *T-LEACH (Threshold LEACH)* protocol CHs function continuously for longer periods. Specifically, cluster heads remain the same for a number of rounds and their replacement takes place once their remaining energy reaches a value that is lower than the defined threshold energy [116].

In *C-LEACH (Cell LEACH)* the FoI is divided into hexagonal cells in order to achieve better coverage. Each cell consists of many nodes that are called cell nodes, and a specific sensor known as cell head. Each cluster is formed by seven adjacent cells and comprises its own CH. Cell members can transmit their sensed data during their allocated time slot, which is determined correspondingly to a time schedule that is assigned to them by their cell head. This schedule exploits the TDMA method. For the transmission of the sensed data to the CH, the whole cell remains powered off except for a cell member that collects the data and forwards them to the cell head. Subsequently the cell head transmits the aggregated data to its corresponding CH and finally the CH transfers the data to the BS by choosing the shortest route between them. This protocol appears to have very high scalability and energy efficiency which is mostly owed to multi-hop communication.

However, the complexity is increased due to the utilization of both cell head and CH nodes [117].

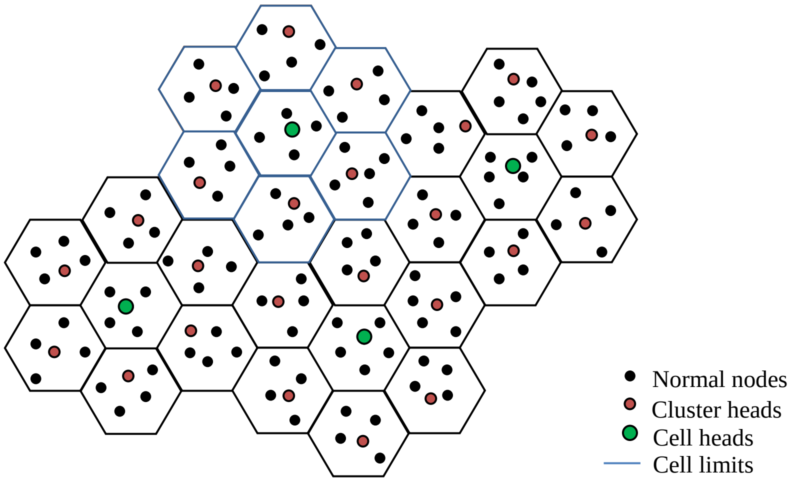

Figure 14: Topology of V-LEACH protocol.

In *LEACH-1R (LEACH One round)* the CHs switch at each round, but only when their energy levels are lower than the threshold. Once the CH's energy is under the threshold, it informs the node with the most powerful signal among the nodes in its cluster that it will be the new CH. Then, the node sends a message to its nearby allocated nodes that encloses the CH's ID, its location, and its remaining energy [118].

In *sLEACH (Solar aware LEACH)* some of the nodes are equipped with solar panels. These nodes perform the power consuming task of being a CH, since their energy reserves are higher than those of normal nodes. The selection of the CHs is based on nodes' solar power status, however nodes running on batteries can also become CHs depending on their energy reserves. The exploitation of energy harvesting devices is applicable in both centralized and distributed clustering. In this protocol, apart from the residual energy and location's information, sensor nodes also send their solar status to the sink. WSNs' performance is directly connected to the number of the nodes having a solar panel adjusted. Hence, the greater the amount of the nodes equipped with solar panels, the greater the network's lifetime. Although sLEACH significantly prolongs the network's lifetime, it does not function that well in the absence of sun. The authors have considered a cluster handover scheme according to which in case a node powered with batteries is acting as a CH and its energy is weakened, a solar-powered node can become the new CH [119].

WLEACH (Wise LEACH) has three different aspects. In the first approach, the average energy of the sensor nodes is considered as the threshold. In order for a node to become a CH, its energy levels must be higher than the threshold. In the second one, geographical routing and multi-hop communication paths are used, while in the last one, the transmitting frequency of the nodes is compared to the processing frequency of the sink. In case the transmitting frequency is higher than the BS processing frequency, more stress is placed on the BS, thus the sensed data are only transmitted when the threshold value is exceeded [120].

In Table 4, a comparison among some of the most important parameters (i.e., scalability, energy efficiency and others) of the aforementioned LEACH successors as summarized by Singh et al. is shown [110].

LEACH Successors	Year	Routing Technique	Clustering	Overhead	Scalability	Emery Efficiency	Complexity	Delay
LEACH-B	Sep 2010	Single-hop	Distributed	High	Low	High	High	High
LEACH-C	Oct 2002	Single-hop	Centralized	Low	Low	High	Moderate	Small
LEACH-CE	Dec 2013	Single-hop	Centralized	Low	Low	Very high	Moderate	Small
LEACH-D	Sep 2010	Multi-hop	Distributed	High	Very high	Very high	Very High	Small
LEACH-L	Nov 2008	Multi-hop	Distributed	High	High	High	High	High
TL-LEACH	Sep 2005	Multi-hop	Distributed	Low	Low	High	Low	Small
I-LEACH	Sep 2009	Single-hop	Distributed	Low	Very high	Very High	High	Small
O-LEACH	Apr 2016	Multi-hop	Distributed	High	High	High	High	High
U-LEACH	Mar 2010	Single-hop	Distributed	Low	Low	High	High	Small
V-LEACH	Jun 2015	Single-hop	Distributed	High	Low	Very high	Very high	High
DL-LEACH	Jul 2016	Multi-hop	Distributed	Moderate	High	High	Low	Moderate
MR-LEACH	Jul 2010	Multi-hop	Distributed	High	High	High	High	High
T-LEACH	Jun 2009	Single-hop	Distributed	Moderate	High	High	High	Small
Cell-LEACH	Feb 2012	Multi-hop	Distributed	Very high	Very high	Moderate	Very high	Moderate
LEACH-1R	Mar 2015	Multi-hop	Distributed	Low	Low	High	High	Small
sLEACH	Jun 2004	Single-hop	Hybrid	High	Moderate	Very high	High	Small
WLEACH	Nov 2012	Multi-hop	Distributed	High	High	Very high	Low	Small

Table 4: Comparison of LEACH’s successors.

It is worth mentioning that there are more successors of LEACH protocol and some of them focus on the energy harvesting and the security such as the EHA-LEACH [121] and the SLEACH [122] respectively. Moreover, others that focus on the mobility of the sensor nodes such as LEACH-M [123], or in data aggregation as DAO-LEACH [124] and several other types.

CHAPTER 4:
Simulations of LEACH Protocol and its Modifications

4.1 Simulators for Wireless Sensor Networks

Typically, engagement with WSNs is associated with the usage of simulating software, since this kind of tool can be used in order to study and evaluate the performance of a WSN in different deployment scenarios, or in order to create new protocols. Despite the ability of such tools to produce reliable data in a short time period, one must take into account that that the simulation results may not emulate the actual behavior of a WSN, or may produce inaccurate results, since in real life existing conditions are usually worse (e.g., wireless communications) than in simulating environments. Moreover, there are unpredictable factors that cannot be predicted in a simulation tool (i.e., the weather conditions, the hardware failures and more). Hence, being aware of the advantages and the constraints of the various simulators is paramount.

4.1.1 Simulating Tools

A significant number of simulating tools have been developed and are exploited as a testbed in order to enhance the performance of network protocols, or to draw conclusions regarding the operation of possible network deployments before proceeding to an actual deployment. Some of the most commonly used in WSNs simulators are presented below.

OMNET++ (Objective Modular Network Testbed in C++) constitutes an open-source simulation framework for communication networks, which is based on the component-C++ programming language [125]. Despite the availability of excellent documentation by OMNet, there are limited resources, source codes and support forums due to the fact of not being that popular yet.

NS-2 (Network Simulator 2) is a widely used open-source event-driven simulation tool that was initially designed for wired networks. However, due to its broad utilization, it was extended in order to support more types of networks, and more specifically, LANs, MANETS (Mobile Ad hoc Networks), and sensor networks [126]. Ns-2 utilizes two programming languages, the C++ and the OTcl (Object oriented Tcl) and there is a significant amount of source codes, resources and forums available. Despite being a powerful simulator, it presents some limitations while simulating WSNs. More specifically, it does not function well for large scale deployments that contain more than 100 nodes, and it lacks in customization [127].

NS-3 (Networks Simulator 3) is an open-source discrete-event simulating software used for network simulations, which was developed in 2008 and its updated versions were launched in 2014. It is not an improvement of NS-2 but a software that was built from scratch. It is based in C++ and Python programming languages and has increased scalability and modularity in comparison with NS-2. Since it is an open-source software, the support is limited and there is lack of libraries concerning WSNs routing protocols [128].

NetSim (Network Simulator) is a commercial discrete event simulation and network modeling tool which supports different types of networks (i.e., MANETs, WSNs, LANs, Cellular GSM and more). It allows the users to exploit both command level and graphical interface in order to deploy, simulate and evaluate the possible scenarios [129].

OPNET (Optimized Network Engineering Tool) is a commercial object-oriented, discrete-event network simulating tool. It is based on the programming languages C and Java and allows the creation of several models and scenarios via a graphical interface which contains certain tools. It is characterized by its extensibility and there is adequate documentation and support available. Nonetheless, there are some drawbacks, since acquiring a license for the software is expensive, its architecture is complicated and it lacks in terms of scalability [127, 130].

MATLAB (Matrix Laboratory) has been developed by MathWorks Inc. and is a commercial programming platform, which is widely used from reasearchers, scientists, engineers, students and others, in order to design and analyze diverse systems. It is a trusted software that can be used for implementations in various sectors such as mathematics, statistics and machine learning, engineering, economics, electronics, telecommunications and more. Furthemore it utilizies its own programming language and comprises a wide variety of toolboxes and hundreds of built-in mathematical functions and provides the ability of creating various graphs. It is also characterized by its flexibility, reliability and its programming capability. MATLAB is also used by researches in order to either create routing protocols for WSNs and to simulate numerous scenarios.

4.1.2 Programming Language C++

One of the main goals of this particular thesis is the creation of a LEACH-based routing protocol for WSNs, which is more energy efficient than LEACH. However, the creation of a protocol demands the utilization of a code development software, which is a feature that most graphical simulators do not offer and the reason why they were not chosen.

C++ is a general-purpose programming language, which is used in developing operating systems, client-server applications, device drivers and embedded firmware. Additionaly, this programming language is behind most web browsers, plenty embedded systems, video games while also being used in software engineering, data structures, and more. Moreover, it supports object-oriented programming (OOPs), whose major principles are inheritance, polymorphism, encapsulation, and abstraction. Its compile and execution time is faster than other programming languages. Furthermore, its compatibility with the programming language C, its portability, and its scalability, as well as the large community of support are listed among the advantages that C++ offers.

Due to the aforementioned advantages C++ programming language was used along with DevC++, which is a full-featured Integrated Development Environment (IDE) and code editor for the code development and simulation purposes of this thesis.

4.2. LEACH Source Code

For the purposes of simulation and the evaluation of LEACH protocol's performance, its source code was necessary. In this respect, LEACH's source code was developed in C++ programming language. The code is divided into five parts:

1. The first part concerns the initialization of the network's parameters. More specifically in this part the field dimensions, the different energy values, the number of cluster heads and the dead nodes, as well as other parameters are clarified.
2. The second part refers to the creation of the WSN and defines how the nodes will be plotted and how far from the base station they will be located. Additionally, the initialization of parameters regarding the state of the node, its coordinates and its ID, the number of rounds that the sensor nodes were elected as CHs and others are performed.
3. The third section deals with the setup phase of LEACH protocol. More particularly, in this part the selection of the cluster heads, the clusters formation and the calculation of the distance between the nodes and their CHs is performed.
4. In the fourth part, which has to do with the steady phase, the energy dissipation for the normal nodes and the cluster heads is calculated.
5. Finally, results regarding the number of operational nodes in each round and the energy consumed during each transmission are printed in a text document allowing further evaluation of LEACH protocol way of operation.

4.3. Simulations of LEACH Protocol and their Results

Several simulations were performed in order to study and evaluate the performance of *LEACH* protocol. In these simulations, the parameters of the network, i.e., the amount of the sensor nodes, their initial energy levels, the location of the sink and the dimensions of the FoI were modified.

In the code used, the plotting of the nodes occurs randomly in every simulation due to the utilization of *"rand"* function. Hence, despite maintaining the network's and energy parameters in each simulation, networks' overall lifetime (which is calculated in rounds) differs.

The purpose of the very first simulations was to calculate the average WSN's lifetime while changing two parameters, the number of nodes and their initial energy. To specify this, three simulation scenarios with a total of 50 nodes, three with a total of 100 sensor nodes and three with 150 nodes and diverse energy values (Eo=1, Eo=2 and Eo=3 Joules) were executed. For each one of these scenarios, thirty repetitions were carried out and the average network's lifespan was then calculated. The simulation results are shown in Table 5.

Number of nodes	n=50			n=100			n=150		
Eo value (in Joules)	Eo=1	Eo=2	Eo=3	Eo=1	Eo=2	Eo=3	Eo=1	Eo=2	Eo=3
WSN's Average lifetime (in rounds)	*890*	*1585*	*2230*	*1214*	*1924*	*2926*	*1368*	*2199*	*3045*

Table 5: Nodes random deployment simulation results.

Upon the evaluation of the simulations' results two important conclusions can be drawn. At first, it is obvious that the greater the initial energy of the sensor nodes, the longer they can perform their tasks, leading to the network's increased lifetime. The second finding is that a WSN's lifespan increases in case of networks with dense deployment. More accurately, the exploitation of a greater number of nodes in a specific FoI prolongs the network's lifetime, since the communication paths are smaller and consequently the energy consumed during data transmission is less comparing to WSNs exploiting less nodes in a FoI with the same dimensions.

Since the deployment of the nodes occurred randomly in the code used, it had to be altered in a way to plot the nodes in specific locations allowing to extract more precise conclusions.

Hence, after adjusting the code in a way that allows the nodes to be plotted in specific coordinates each time, in the next stage of simulations the amount of the sensor nodes was set to 100, while base station's coordinates were changed in each repetition. The results of the WSNs' performance are summarized in Table 6 and three of the plots with diverse sink's coordinates are illustrated in Figures 15-17.

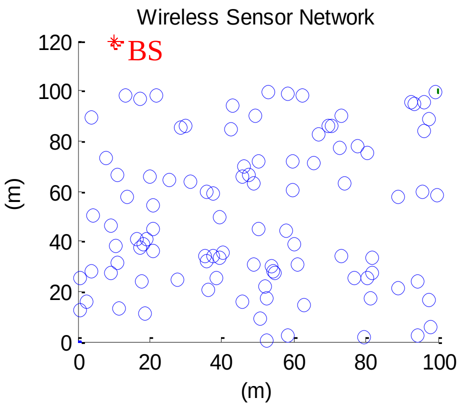

Figure 15: Sink coordinates x=10, y=120

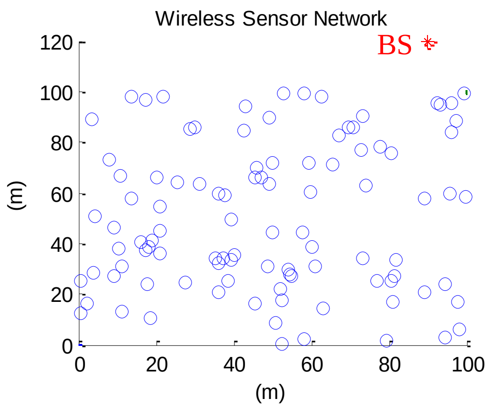

Figure 16: Sink coordinates x=90, y=120

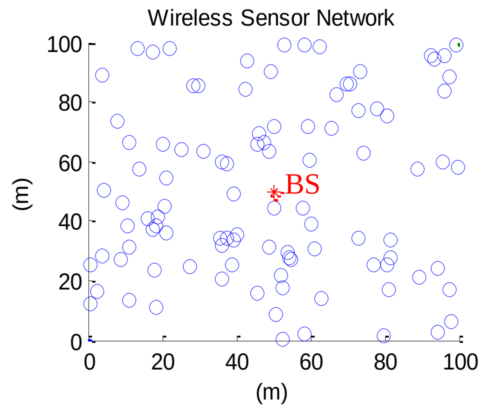

Figure 17: Sink coordinates x=50, y=50

Coordinates of the sink	x	10	90	50	50	50	50	50	50	50
	y	120	120	110	130	150	50	200	230	250
WSN's lifetime (in rounds)		2867	3393	3381	3513	2783	3662	1939	1715	1492

Table 6: Nodes specific deployment simulation results.

According to the data depicted in Table 6, the overall endurance of a WSN is connected to the distance between the nodes and the base station, as well as its location in the network, namely whether it will be located inside or outside the limits of the FoI. Considering that the data are transmitted to the base station through the cluster heads, the closer the CHs are to the base station, the longer the network will last. Oppositely, in case the cluster heads are far from the BS, the transmissions are achieved through longer communication paths, leading to nodes' energy earlier dissipation.

As shown in Table 6, the network lasts longer in case the BS is in the middle of the FoI, or at the coordinates x=50, and y=110. On the contrary, as the distance of the BS from the X axis is increased, the network's lifetime is reduced. Concluding, as the sink is closer to the FoI in regards of Y axis, the communication paths are reduced, and the network's endurance can be improved. In regards with the X axis, sensor nodes consume their energy levels faster, since those located in the opposite side of the BS's location need to consume more energy to transfer their data to the CHs and accordingly their CHs consume more energy to transmit the data to the sink.

From the results that emerged from the simulations, it is concluded that:

The overall endurance of a WSN is connected to the number of nodes and their initial energy reserves. More specifically, the greater the number of nodes and their initial energy, the greater the lifetime of the WSN is.

- ➢ The lifespan of the network is related to the distance between the nodes and the base station and its location in the network, namely whether it will be located inside or outside the limits of the FoI. Considering that the data are transmitted to the base station through the cluster heads, the closer the CHs are to the base station, the longer the network will last. Oppositely, in case the cluster heads are far from the BS, the transmissions will be achieved through longer communication paths, leading to nodes' energy earlier dissipation.
- ➢ Placing the BS in the middle of the FoI does not entail the optimum deployment, since the network's lifetime depends on the distance between the BS and the CHs. Hence, in case the CHs are not close to FoI's center, the BS must be placed in a location with a greater amount of nearby allocated CHs.
- ➢ In cases where the number of nodes is fixed, the greater the dimensions of the FoI are, the earlier the energy of the network gets depleted.

4.4 Modifications of LEACH Protocol

In the next stage, an attempt to create a LEACH-based protocol that would be more energy efficient than LEACH was undertaken. Therefore, three modifications of LEACH protocol (LEACH-TCH, LEACH-mTCH, LEACH-qmTCH) were developed, to compare the operation of LEACH protocol to the modified ones. Moreover, the source code of an already known successor of LEACH, the LEACH-B protocol was created. In what follows, a description of the modifications developed in this thesis, is presented.

4.4.1 LEACH-TCH

In **LEACH-TCH** (Transitional Cluster Head) the steady phase remains the same as in LEACH protocol, while the setup phase of LEACH is modified by adding a transitional cluster head (TCH) node between the cluster heads and the base station. This particular CH collects the aggregated data from the rest of the CHs. According to this modification two additional criteria are taken into consideration. More specifically, upon CHs election, the CH with the highest energy reserves (TCH) is chosen and transmits an advertisement message to the rest of the CHs informing them about its status. Then the distance between the CHs and the BS is compared to the distance between the TCH and the BS. In the case that the distance between a CH and the BS is less than the distance between the TCH and the BS, data are transmitted directly from the CH to the BS, thus bypassing the TCH. On the contrary, in case the distance between a CH and the BS is greater than the distance between the TCH and the BS, the data are transmitted from the specific CH to the TCH and then they are forwarded to the sink through this node. This way a greater degree of aggregation is achieved.

4.4.2 LEACH-mTCH

LEACH-mTCH (multiple Transitional Cluster Heads) constitutes an alteration of LEACH-TCH protocol. Specifically, one or more transitional cluster head (TCH) nodes are added between the cluster heads and the base station. The number of the occurring transitional CHs is calculated based on the number of the CHs. More precisely, the number of the TCHs in each round is equal to the amount of the existing CHs divided by number 5. Based on experimental data collected throughout various simulations this number turns out to be the most efficient one. TCHs collect the aggregated data from their nearby allocated CHs. Upon CHs election, the designated numbers of CHs with the highest energy reserves (TCHs) are chosen and transmit advertisement messages to the rest of the CHs informing them about their status. Each CH compares its distance between the TCH and the BS. In case that the CH is closer to the BS than the TCH is, data are routed directly from the CH to the BS. Conversely, when the distance between a CH and the BS is greater than the distance between the TCH and the BS, the data are sent from the specific CH to its predefined TCH and then they are forwarded to the sink through it.

4.4.3 LEACH-qmTCH

In **LEACH-qmTCH** (quadrant multiple Transitional Cluster Heads) the FoI is divided in four quarters. According to this protocol, in each quarter, the CH with the highest amount of energy is selected as the transitional CH (TCH) between the BS and the CHs. Consequently, four TCHs are elected at each round. The CHs that belong to each quarter, transmit their aggregated data to their corresponding TCH and accordingly, data are forwarded to the BS via this node.

4.5 Simulations Results and Comparison of LEACH Protocol and its Modifications

Several simulations were performed in order to study and evaluate the performance of the modifications of LEACH protocol that were created. It is highlighted that multiple scenarios with different network parameters were conducted and that the coordinates of the nodes within the FoI occurred randomly. To achieve better results, 30 repetitions of each scenario were performed and the results regarding the network's lifetime that are presented in the following tables are the median values of these repetitions. The optimum protocol for each scenario is highlighted with green color.

1. Parameters: sinkx=50, sinky=200, Eo=2 Joule, grid dimensions: x=100, y=100.

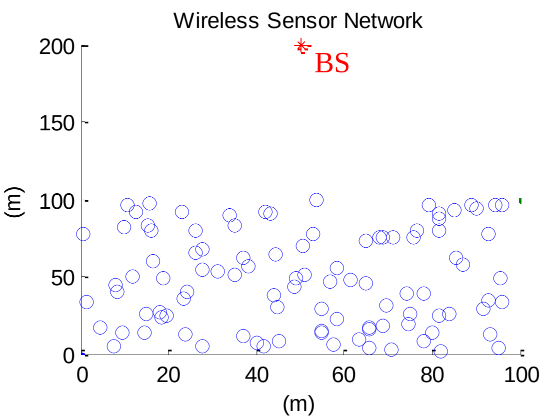

Figure 18: Scenario 1st network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	1251	1263	1299	1280	1407
n=50	1572	1578	1677	1645	1880
n=75	1786	1827	1987	1836	2159
n=100	1924	1957	2322	2024	2577
n=200	2367	2444	2999	2593	3419
n=300	2649	2727	3337	2866	3783
n=400	2838	2933	3534	3090	4108
n=500	2904	3028	3680	3171	4224
n=1000	3221	3375	4012	3518	4451

Table 7: Scenario 1st simulation's results.

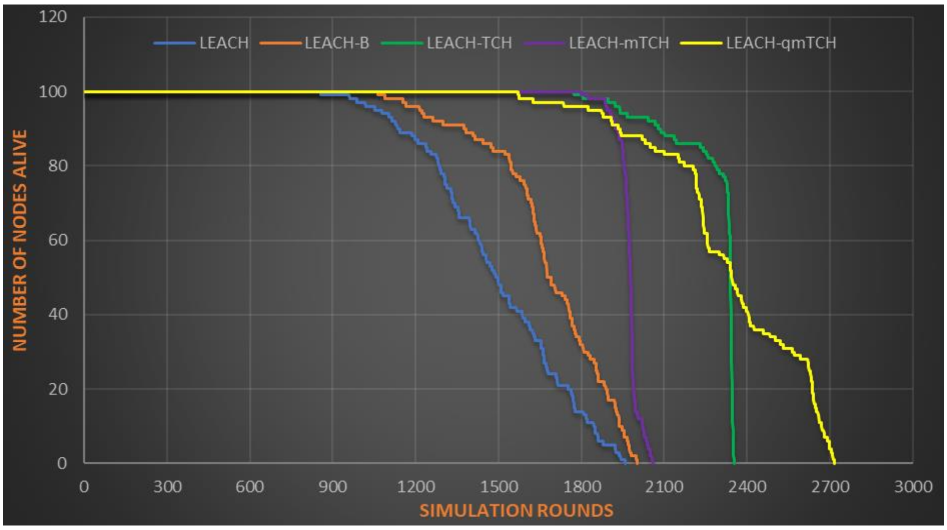

Figure 19: Number of nodes alive vs simulation rounds in 1st scenario.

2. Parameters: sinkx=50, sinky=300, Eo=2 Joule, grid dimensions: x=100, y=100.

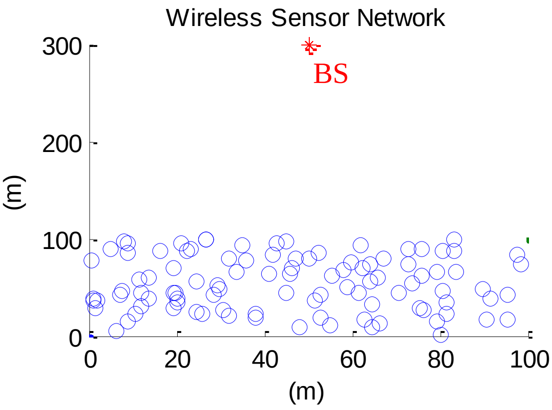

Figure 20: Scenario 2nd network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	682	803	855	804	983
n=50	815	992	1239	1203	1434
n=75	928	1086	1537	1245	1842
n=100	1012	1189	1955	1373	2250
n=200	1230	1372	2658	1694	3106
n=300	1365	1456	3028	1702	3580
n=400	1445	1530	3265	1797	3824
n=500	1503	1575	3430	1833	4033
n=1000	1597	1668	3821	1928	4382

Table 8: Scenario 2nd simulation's results.

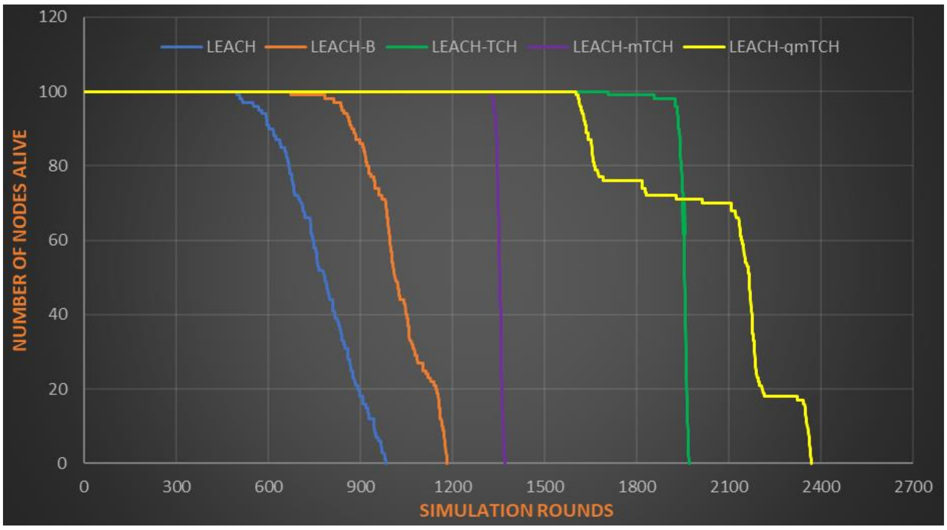

Figure 21: Number of nodes alive vs simulation rounds in 2nd scenario.

3. Parameters: sinkx=50, sinky=100, Eo=2 Joule, grid dimensions: x=100, y=100.

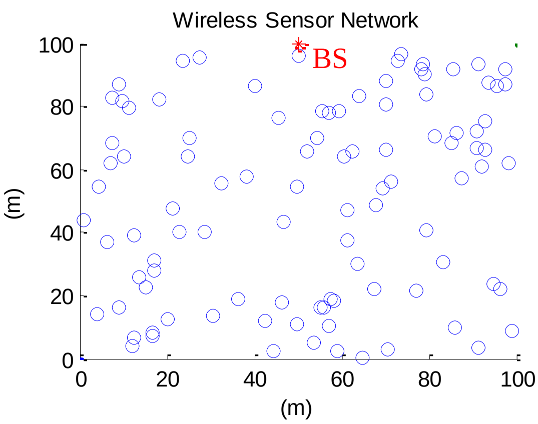

Figure 22: Scenario 3rd network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	2341	2262	2231	2246	2279
n=50	2652	2392	2316	2334	2401
n=75	2943	2588	2525	2608	2579
n=100	3265	3212	2934	3105	2999
n=200	3792	3894	3638	3936	3650
n=300	4165	4410	4094	4458	4112
n=400	4493	4662	4257	4706	4300
n=500	4767	5012	4566	5089	4581
n=1000	5303	5646	4847	5679	4923

Table 9: Scenario 3rd simulation's results.

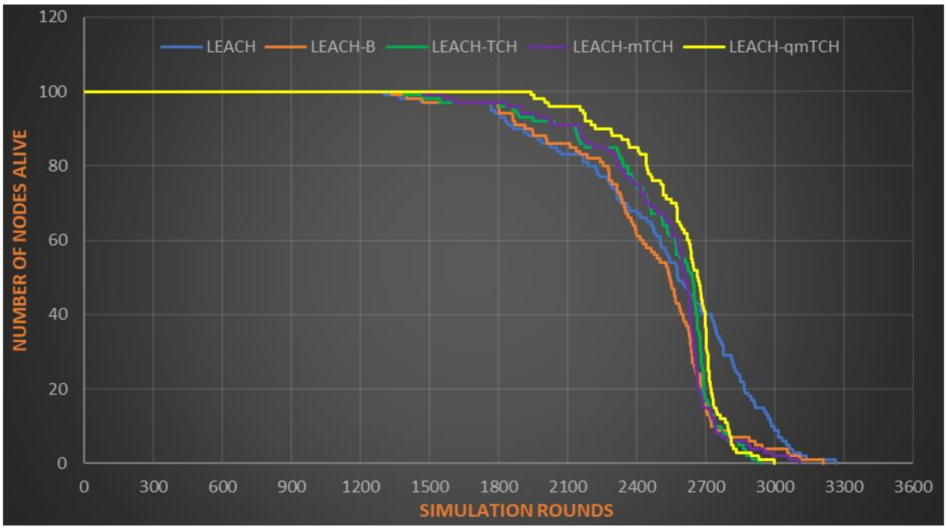

Figure 23: Number of nodes alive vs simulation rounds in 3rd scenario.

4. Parameters: sinkx=50, sinky=50, Eo=2 Joule, grid dimensions: x=100, y=100.

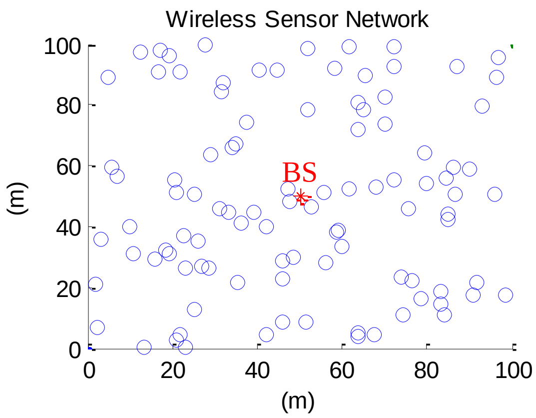

Figure 24: Scenario 4th network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	2572	2551	2511	2479	2499
n=50	2873	2547	2513	2583	2501
n=75	2949	2667	2619	2615	2613
n=100	3215	3063	2994	3013	3021
n=200	3845	4305	3746	4132	3804
n=300	4663	4673	4016	4731	4087
n=400	4423	5034	4532	5117	4493
n=500	4519	5170	4650	5268	4504
n=1000	4987	5795	4823	5493	4795

Table 10: Scenario 4th simulation's results.

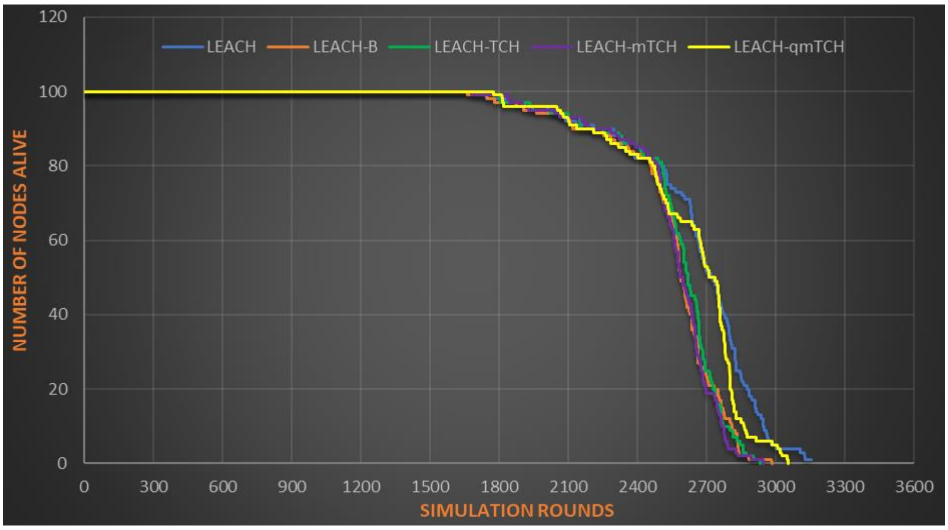

Figure 25: Number of nodes alive vs simulation rounds in 4th scenario.

5. Parameters: sinkx=10, sinky=120, Eo=2 Joule, grid dimensions: x=100, y=100.

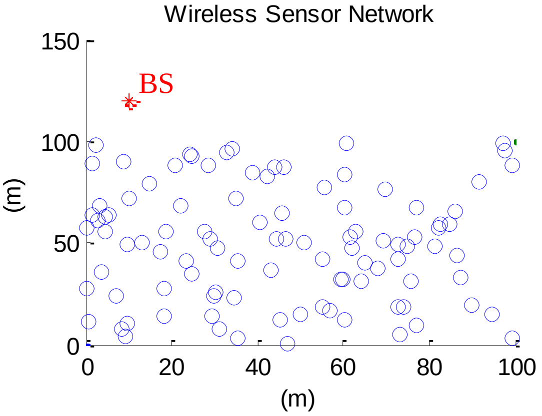

Figure 26: Scenario 5th network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	1911	1864	1847	1857	2039
n=50	2455	2183	2163	2150	2216
n=75	2576	2406	2354	2406	2555
n=100	2780	2652	2663	2630	2889
n=200	3485	3454	3392	3489	3522
n=300	3906	3953	3745	4032	3905
n=400	4210	4235	4009	4395	4057
n=500	4643	4701	4302	4803	4414
n=1000	4975	5432	4374	5372	4489

Table 11: Scenario 5th simulation's results.

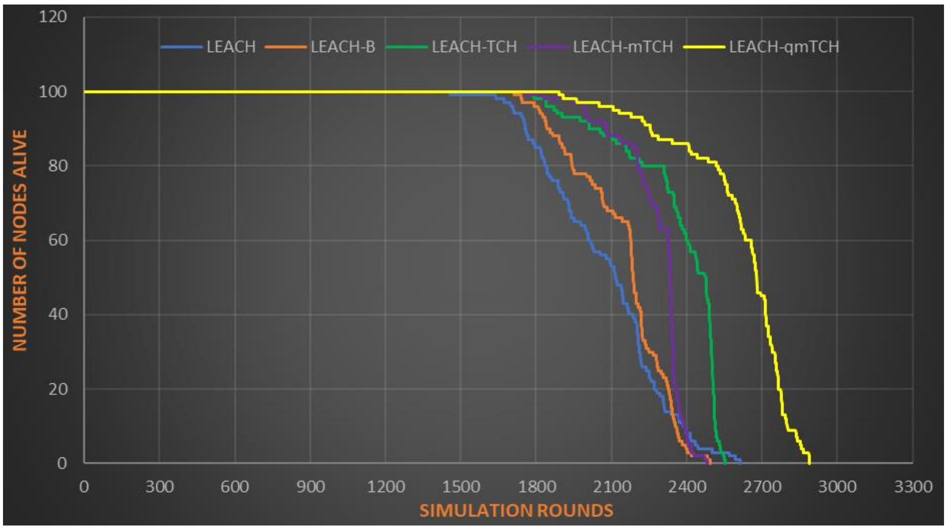

Figure 27: Number of nodes alive vs simulation rounds in 5th scenario.

6. Parameters: sinkx=90, sinky=40, Eo=2 Joule, grid dimensions: x=100, y=100.

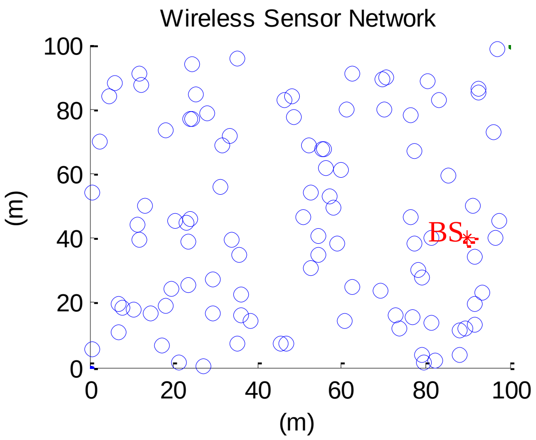

Figure 28: Scenario 6th network's deployment.

	WSN's Lifetime (Rounds)				
Nodes	LEACH	LEACH-B	LEACH-TCH	LEACH-mTCH	LEACH-qmTCH
n=25	2494	2308	2265	2335	2389
n=50	2778	2486	2450	2492	2511
n=75	2994	2694	2619	2662	2679
n=100	3299	2968	2876	2896	2930
n=200	3780	4045	3952	4145	3722
n=300	4116	4321	4314	4464	4129
n=400	4389	4719	4641	4729	2567
n=500	4859	5210	4987	5196	4823
n=1000	5265	5769	5336	5626	5245

Table 12: Scenario 6th simulation's results.

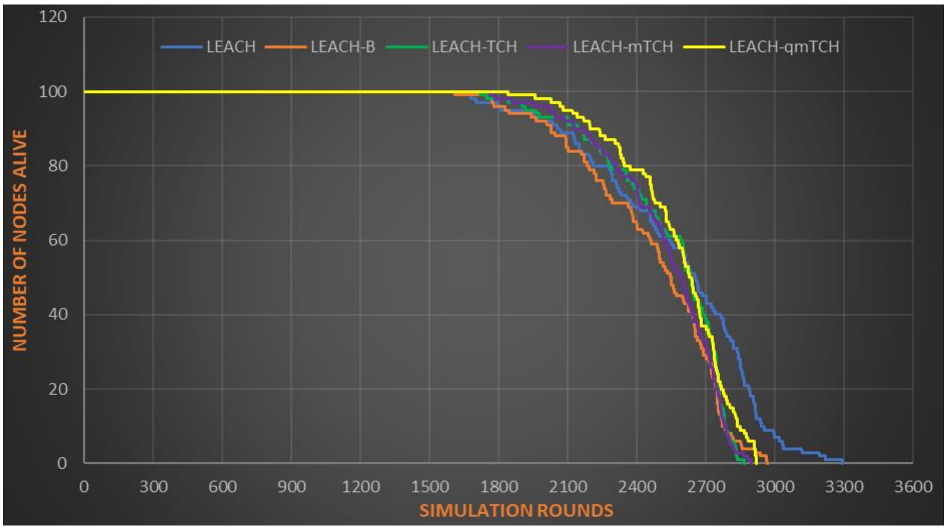

Figure 29: Number of nodes alive vs simulation rounds in 6th scenario.

After comparing LEACH protocol, to LEACH-B and the three modifications developed (LEACH-TCH, LEACH-mTCH, LEACH-qmTCH), the following conclusions were conducted:

- In cases where the base station is located outside the sensing field (where the sensor nodes are deployed) LEACH-qmTCH protocol appears to be more energy efficient than the rest of the protocols. To be precise, in cases where the network consists of 100 nodes, LEACH-qmTCH prolongs the lifetime for approximately 650 and 600 simulation rounds compared to LEACH and LEACH-B protocol respectively. For networks with greater number of nodes, their lifetime could even be prolonged for 1200 rounds (case of 1000 nodes) in comparison with LEACH protocol. Additionally, protocols LEACH-TCH and LEACH-mTCH perform better than LEACH and LEACH-B.
- When the sink is located even further outside the network, all three modifications appear to have much better results. More specifically, LEACH-qmTCH improves the lifetime of a WSN for around 1250 rounds in case of a network with 100 nodes, and 2800 rounds in case of a network with 1000 sensor nodes. Similarly, in deployments with 100 sensor nodes, LEACH-TCH and LEACH-mTCH prolong the network's lifetime for 900 and 300 rounds respectively.
- If the sink is placed in the center of the sensing area, LEACH protocol performs better than the ones compared to it during the simulations for deployments with 100 sensor nodes, while for deployments with more than 250 nodes, LEACH-mTCH preserves the network's overall energy for longer periods.
- In cases where the base station is located randomly inside the sensing area or outside but in close distance to it, LEACH-mTCH protocol performs better than the others, for deployments with more than 200 sensor nodes.

Compared to LEACH protocol the three developed modifications present significant improvement in regard to energy saving and the overall network lifetime, since better data aggregation is achieved due to the utilization of additional cluster heads (transitional cluster heads). This is especially observed in deployments with a larger number of nodes. However, one major drawback is that they exhibit increased complexity.

Among the three modifications, LEACH-qmTCH appears to perform better and achieves greater energy saving in cases where the BS is placed far from the sensing area, while LEACH-mTCH performs better in cases when there is large amount of sensor nodes and when the BS is located inside the sensing area. The selection of the most suitable protocol depends on the parameters and the deployment of each network.

CHAPTER 5: EPILOGUE

5.1 Synopsis

This thesis focused on the methods that are mostly applied in WSNs to make their operation energy efficient. These methods aim to lessen the nodes' battery dissipation while performing their tasks. Protocols using sleep/wake up schemes and low power transceivers, as well as energy efficient routing are among the energy approaches that lead to energy saving. Although most of the mechanisms summarized in this thesis can significantly reduce power dissipation, energy saving is still a challenging task that gathers the interest of many researchers trying to propose even more efficient techniques.

Furthermore, this study explored the energy efficient routing protocol LEACH and some of the most important successors of it and a detailed comparison between them was presented. There are successors that utilize single-hop or multi-hop communication paths, and others that exploit both. Some of the successors focus on finding better routing paths, counting in the energy consumed based in the distance, others utilize relay nodes to act as interconnection points between the BS and the CHs. Additionally, there are others that take advantage of nodes' mobility, or of energy harvesting devices that can be adjusted to them.

Finally, three modifications of LEACH protocol were developed (LEACH-TCH, LEACH-mTCH and LEACH-qmTCH) and their performance was evaluated in comparison with LEACH and LEACH-B protocols.

It is highlighted that some of the outcomes of this thesis have already been published in [131], [132], and [133].

5.2 Conclusions

Despite the contribution of WSNs to a continuously growing variety of applications, their deployment faces several problems with those caused by the inherent energy limitations of the sensor nodes to be considered as the most significant. This research thesis investigated all of the existing hardware-based and algorithm-based methods that aim to support the energy sustainability of WSNs, via energy saving, energy harvesting and energy transfer.

Although the current mechanisms are evinced to be quite effective, there are still many weaknesses that are associated with their utilization. For this reason, novel research works have to be conducted. Additionally, although some of these methods can be combined in order to accomplish enhanced performance of both the individual network nodes and the overall network, the achievement of this combination is not straightforward. Likewise, the collaboration of energy management methods of this type along with methods that pursue the enhancement of the performance of WSNs regarding metrics other than energy is a very challenging topic that needs thorough research study. Furthermore, due to the continuous growth of the range of applications of WSNs that in many cases have diverse requirements, novel efficient methods for energy sustainability need to be pursued.

Among other techniques, the energy efficient routing technique can lead to a wireless sensor network's greater energy saving. One of the initially developed hierarchical routing protocols, LEACH protocol, was studied thoroughly in this thesis. Although this protocol achieves energy saving in WSNs, there is a series of drawbacks, such as the exploitation of single-hop paths which makes LEACH protocol unsuitable for larger scale networks, and the utilization of dynamic clustering that implies extra overhead that could raise energy consumption. Therefore, several successors of LEACH protocol have occurred throughout the years, attempting to offer greater energy efficiency to wireless sensor networks.

Based on the simulation results that were extracted, the three LEACH protocol modifications (LEACH-TCH, LEACH-mTCH, LEACH-qmTCH) that were developed, perform better in cases where the sink is located far from the sensing area, while LEACH is more suitable when the sink is located close to the sensing area and the network consists of a smaller amount of nodes.

Future research could elaborate on developing a protocol, which will exploit the energy resources of sensor nodes more efficiently when compared to LEACH protocol, leading to WSN's overall lifetime prolongment at any network deployment.

5.3 General Challenges and Open Research Issues

According to this thesis, that explicitly regards either the hardware-based or the algorithm-based methods for energy sustainability in WSNs, there are some more challenges that are posed by general considerations that trigger corresponding issues of future research.

In addition, the development of the most of the abovementioned methodologies is based on theoretical assumptions that may be impractical in real-life scenarios. For instance, in most approaches the network nodes are assumed to be homogenous, i.e., to have the same operational and structural features. This hypothesis simplifies their research study, but it may lead to unrealistic results because the existence of heterogeneous WSNs is toocommon to overlook. This issue has to be handled by novel research works [134-139].

Similarly, in most models there is lack of mobility considerations, although mobile wireless sensor networks (MWSNs) have superior capabilities than static WSNs. On the other hand, energy management is inherently more complex to both study and implement in MWSNs thus necessitating the development of novel research in this direction [140-142].

Furthermore, the majority of methods for energy sustainability consider two dimensional networks. Hence, more research works should be conducted regarding three dimensional WSNs [143, 144].

Likewise, due to the handling of multimedia data, Wireless Multimedia Sensor Networks (WMSNs) have special needs in terms of both the nature (i.e., images, video, etc.) and the volume of data and at the same time extremely high requirements regarding QoS metrics that need to be supported [145-151].

Another issue is that research in many of the abovementioned methodologies is based on tests performed by using computer aided simulations. However, some recent technological advances (e.g., in energy harvesting and energy transfer) are not sufficiently supported by the existing simulation platforms in terms of corresponding energy models of high accuracy [8]. Likewise, there is lack of specialized equipment for wireless energy transfer in corresponding emulation tests performed using testbeds, due to its high cost [8]. Therefore, existing simulation and emulation tools have to be enhanced.

Additionally, Artificial Intelligence and Computational Intelligence can provide extremely good support to the development of mechanisms for energy sustainability in WSNs that are able to self-learn and thus easily adapt to any alterations that dynamically take place in the structure or/and operation of WSNs. Specifically, the use of methods, such as Machine Learning, Fuzzy Logic, Neural Networks, Artificial Immune Algorithms, Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization, is very promising [152-161].

Moreover, due to the scientific and technological advancements that are performed, there is a continuous growth of applications that incorporate the usage of Aerial Wireless Sensor Networks (AWSNs), Wireless Underground Sensor Networks (WUSNs) and Underwater Wireless Sensor Networks (UWSNs). However, the majority of the aforementioned methodologies that pursue energy sustainability in WSNs have been designated to be applied in terrestrial WSNs and cannot be used in non-terrestrial WSNs because of the extraordinary conditions that exist in such networks. For this reason, novel research efforts have to support energy sustainability in non-terrestrial WSNs, too [162-166].

Going one step further, in order to achieve high sustainability along with optimal overall performance in a WSN, metrics other than energy should be considered, too. For this reason, hybrid schemes have to be developed. Specifically, the extension of network connectivity should be preserved because whenever a node loses its connection with its neighboring nodes due to either its malfunction or its energy depletion, there is a certain increase of energy cost for the communications of the remaining active nodes [167, 168].

Furthermore, in order to achieve the optimal utilization of nodes existing in a WSN and thus the optimization of the overall deployment of the network, the maximization of coverage is necessitated [169-171].

Additionally, congestion avoidance and congestion control [172-175] mechanisms should be used because congestion obstructs communication, generates packet losses and thus imposes packet retransmissions that exhaust the energy of nodes. Moreover, schemes for the establishment of QoS in terms of general or specific performance metrics are required [176, 177].

Furthermore, security schemes for WSNs to assure confidentiality, authentication, integrity, availability, and freshness are required [178-180].

However, the achievement of energy efficiency along with other performance metrics is not a trivial task to accomplish. This is because the conditions that must be fulfilled are not only several, but they also are opposing in many cases. Likewise, the concurrent deployment of different methods for energy sustainability may also be obstructed due to the opposing requirements that they may have. For this reason, multi-objective optimization algorithms that pursue the concurrent achievement of multiple criteria [181, 182] have to be developed.

REFERENCES

[1] Akyildiz, I.F.; Su, W.; Sankarasubramaniam, Y.; Cayirci, E. Wireless Sensor Networks: A Survey. Comput. Netw. 2002, 38, 393-422.

[2] Yick, J.; Mukherjee, B.; Ghosal, D. Wireless Sensor Network Survey. Comput. Netw. 2008, 52, 2292-2330.

[3] Wang, Q.; Balasingham, I. Wireless sensor networks-an Introduction. In Wireless Sensor Networks: Application-Centric Design; InTechOpen: London, UK, 2010; pp. 1-14.

[4] Lee, J.-W.; Lee, J.-Y.; Lee, J.-J. Jenga-Inspired Optimization Algorithm for Energy-Efficient Coverage of Unstructured WSNs. IEEE Wireless Communications Letters 2013, 2 (1), 34-37.

[5] Ali, A.; Ming, Y.; Chakraborty, S.; Iram, S. A Comprehensive Survey on Real-Time Applications of WSN. Future Internet 2017, 9, 77. https://doi.org/10.3390/fi9040077.

[6] Kandris, D.; Nakas, C.; Vomvas, D.; Koulouras, G. Applications of Wireless Sensor Networks: An Up-To-Date Survey. Appl. Syst. Innov. 2020, 3, 14.

[7] Pantazis, N.; Kandris, D. Power Control Schemes in Wireless Sensor Networks. WSEAS Trans. Commun. 2005, 4, 1100-1107.

[8] Engmann, F.; Katsriku, F.A.; Abdulai, J.-D.; Adu-Manu, K.S.; Banaseka, F.K. Prolonging the Lifetime of Wireless Sensor Networks: A Review of Current Techniques. Wirel. Commun. Mob. Comput. 2018, 2018, 8035065.

[9] Rezaei, Z. Energy Saving in Wireless Sensor Networks. Int. J. Comput. Sci. Eng. Surv. 2012, 3, 23-37.

[10] Rault, T.; Bouabdallah, A.; Challal, Y. Energy Efficiency in Wireless Sensor Networks: A Top-down Survey. Comput. Netw. 2014, 67, 104-122.

[11] Khan, J.A.; Qureshi, H.K.; Iqbal, A. Energy Management in Wireless Sensor Networks: A Survey. Comput. Electr. Eng. 2015, 41, 159-176.

[12] Anastasi, G.; Conti, M.; Di Francesco, M.; Passarella, A. Energy Conservation in Wireless Sensor Networks: A Survey. Ad Hoc Netw. 2009, 7, 537-568.

[13] Patel, H.; Shah, V. A review on energy consumption and conservation techniques for sensor node in WSN. In Proceedings of the IEEE 2016 International Conference on Signal Processing, Communication, Power, and Embedded System (SCOPES), Paralakhemundi, India, 3-5 October 2016; pp. 594-599.

[14] Stankovic, J.A.; He, T. Energy Management in Sensor Networks. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 2012, 370, 52-67.

[15] Warneke, A.; Pister, J. MEMS for distributed wireless sensor networks. In Proceedings of the 9th IEEE International Conference on Electronics, Circuits, and Systems, Dubrovnik, Croatia, 15-18 November 2002; pp. 291-294.

[16] Gamba, P.; Goldoni, E.; Savazzi, P.; Arpesi, P.G.; Sopranzi, C.; Dufour, J.F.; Lavagna, M. Wireless passive sensors for remote sensing of temperature on aerospace platforms. IEEE Sens. J. 2014, 14, 3883-3892.

[17] Pouwelse, J.; Langendoen, K.; Sips, H. Dynamic voltage scaling on a low-power microprocessor. In Proceedings of the 7th Annual International Conference on Mobile Computing and Networking-MobiCom'01, Rome, Italy, 16-21 July 2001.

[18] Kulau, U.; Büsching, F.; Wolf, L. A Node's life: Increasing WSN lifetime by dynamic voltage scaling. In Proceedings of the 2013 IEEE International Conference on Distributed Computing in Sensor Systems, Cambridge, MA, USA, 8-11 July 2013; pp. 241-248.

[19] Nikolić, G.; Nikolić, T.; Stojčev, M.; Petrović, B.; Jovanović, G. Battery capacity estimation of wireless sensor node. In Proceedings of the IEEE 30th International Conference on Microelectronics (MIEL), Beirut, Lebanon, 9-11 October 2017; pp. 279-282.

[20] Narayanaswamy, S.; Schlueter, S.; Steinhorst, S.; Lukasiewycz, M.; Chakraborty, S.; Hoster, H. On Battery Recovery Effect in Wireless Sensor Nodes. ACM Trans. Des. Autom. Electron. Syst. 2016, 21, 2890501.

[21] Panatik, K.Z.; Kamardin, K.; Shariff, S.A.; Yuhaniz, S.S.; Ahmad, N.A.; Yusop, O.M.; Ismail, S. Energy harvesting in wireless sensor networks: A Survey. In Proceedings of the 2016 IEEE 3rd International Symposium on Telecommunication Technologies (ISTT), Kuala Lumpur, Malaysia, 28-30 November 2016.

[22] Shaikh, F.K.; Zeadally, S. Energy Harvesting in Wireless Sensor Networks: A Comprehensive Review. Renew. Sustain. Energy Rev. 2016, 55, 1041-1054.

[23] Singh, J.; Kaur, R.; Singh, D. Energy Harvesting in Wireless Sensor Networks: A Taxonomic Survey. Int. J. Energy Res. 2020, 45, 118-140.

[24] Tony, A.; Hiryanto, L. A Review on Energy Harvesting and Storage for Rechargeable Wireless Sensor Networks. IOP Conf. Ser. Mater. Sci. Eng. 2019, 508, 012120.

[25] Williams, A.J.; Torquato, M.F.; Cameron, I.M.; Fahmy, A.A.; Sienz, J. Survey of Energy Harvesting Technologies for Wireless Sensor Networks. IEEE Access 2021, 9, 77493-77510.

[26] Ruan, T.; Chew, Z.J.; Zhu, M. Energy-Aware Approaches for Energy Harvesting Powered Wireless Sensor Nodes. IEEE Sens. J. 2017, 17, 2165-2173.

[27] Sudevalayam, S.; Kulkarni, P. Energy Harvesting Sensor Nodes: Survey and Implications. IEEE Commun. Surv. Tutor. 2011, 13, 443-461.

[28] Sah, D.K.; Amgoth, T. Renewable Energy Harvesting Mechanisms in Wireless Sensor Networks: A Survey. Inf. Fusion 2020, 63, 223-247.

[29] Adu-Manu, K.S.; Adam, N.; Tapparello, C.; Ayatollahi, H.; Heinzelman, W. Energy-harvesting wireless sensor networks (EH-WSNs): A review. ACM Trans. Sens. Netw. 2018, 14, 1-50.

[30] Khriji, S.; El Houssaini, D.; Kammoun, I.; Kanoun, O. Energy-efficient methods in wireless sensor networks, technology, components, and system design. In Energy Harvesting for Wireless Sensor Networks, 1st ed.; Kanoun, O., Ed.; De Gruyter: Berlin, Germany, 2018; pp. 287-304.

[31] Barman, S.D.; Reza, A.W.; Kumar, N.; Karim, M.E.; Munir, A.B. Wireless Powering by Magnetic Resonant Coupling: Recent Trends in Wireless Power Transfer System and Its Applications. Renew. Sustain. Energy Rev. 2015, 51, 1525-1552.

[32] Mou, X.; Sun, H. Wireless power transfer: Survey and roadmap. In Proceedings of the 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, UK, 11-14 May 2015.

[33] Fahmy, H.M.A. Protocol stack of WSNs. In Concepts, Applications, Experimentation and Analysis of Wireless Sensor Networks; Springer: Cham, Switzerland, 2020; pp. 53-66.

[34] Gupta, S.K.; Singh, S. Survey on Energy Efficient Dynamic Sink Optimum Routing for Wireless Sensor Network and Communication Technologies. Int. J. Commun. Syst. 2022, 35, e5194.

[35] Landaluce, H.; Arjona, L.; Perallos, A.; Falcone, F.; Angulo, I.; Muralter, F. A Review of IoT Sensing Applications and Challenges Using RFID and Wireless Sensor Networks. Sensors 2020, 20, 2495.

[36] Zhongmin, P.; Deng, Z.; Yang, B.; Cheng, X. Application-oriented wireless sensor network communication protocols and hardware platforms: A survey. In Proceedings of

the 2008 IEEE International Conference on Industrial Technology, Chengdu, China, 21-24 April 2008.
[37] Khalifeh, A.; Aldahdouh, K.A.; Darabkh, K.A.; Al-Sit, W. A Survey of 5G Emerging Wireless Technologies Featuring LoRaWAN, Sigfox, NB-IoT and LTE-M. In Proceedings of the 2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), Xi'an, China, 23-25 October 2019.
[38] Ikpehai, A.; Adebisi, B.; Rabie, K.M.; Anoh, K.; Ande, R.E.; Hammoudeh, M.; Gacanin, H.; Mbanaso, U.M. Low-Power Wide Area Network Technologies for Internet-of-Things: A Comparative Review. IEEE Int. Things J. 2019, 6, 2225-2240.
[39] Mekki, K.; Bajic, E.; Chaxel, F.; Meyer, F. A Comparative Study of LPWAN Technologies for Large-Scale IoT Deployment. ICT Express 2019, 5, 1-7.
[40] Nakas, C.; Kandris, D.; Visvardis, G. Energy Efficient Routing in Wireless Sensor Networks: A Comprehensive Survey. Algorithms 2020, 13, 72.
[41] Sahar, G.; Bakar, K.A.; Rahim, S.; Khani, N.A.K.K.; Bibi, T. Recent Advancement of Data-Driven Models in Wireless Sensor Networks: A Survey. Technologies 2021, 9, 76.
[42] Guo, P.P.; Cao, J.; Liu, X. Lossless In-Network Processing in WSNs for Domain-Specific Monitoring Applications. IEEE Trans. Ind. Inform. 2017, 13, 2130-2139.
[43] Wu, M.; Tan, L.; Xiong, N. Data Prediction, Compression, and Recovery in Clustered Wireless Sensor Networks for Environmental Monitoring Applications. Inf. Sci. 2016, 329, 800-818.
[44] Singh, P.K.; Bhargava, B.K.; Paprzycki, M.; Kaushal, N.C.; Hong, W.C. Handbook of Wireless Sensor Networks: Issues and Challenges in Current Scenario's; Springer International Publishing: Cham, Switzerland, 2020.
[45] Srbinovski, B.; Magno, M.; O'Flynn, B.; Pakrashi, V.; Popovici, E. Energy aware adaptive sampling algorithm for energy harvesting wireless sensor networks. In Proceedings of the IEEE Sensor Applications Symposium, Zadar, Croatia, 13-15 April 2015; pp. 1-6.
[46] Oren, G.; Barenboim, L.; Levin, H. Adaptive Distributed Hierarchical Sensing algorithm for reduction of wireless sensor network cluster-heads energy consumption. In Proceedings of the 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, 26-30 June 2017; pp. 980-986.
[47] Sathe, S.; Papaioannou, T.G.; Jeung, H.; Aberer, K. A survey of model-based sensor data acquisition and management. In Managing and Mining Sensor Data; Springer: Boston, MA, USA, 2013; 9-50.
[48] Fahmy, H.M.A. Wireless Sensor Networks: Energy Harvesting and Management for Research and Industry; Springer: Cham, Switzerland, 2020; pp. 109-110.
[49] Aiello, O.; Crovetti, P.; Lin, L.; Alioto, M. A PW-Power Hz-Range Oscillator Operating with a 0.3-1.8-V Unregulated Supply. IEEE J. Solid-State Circuits 2019, 54, 1487-1496.
[50] Aiello, O.; Crovetti, P.; Alioto, M. Wake-Up Oscillators with pW power consumption in dynamic leakage suppression logic. In Proceedings of the 2019 IEEE International Symposium on Circuits and Systems (ISCAS), Sapporo, Japan, 26-29 May 2019; pp. 1-5.
[51] Demirkol, I.; Ersoy, C.; Onur, E. Wake-up Receivers for Wireless Sensor Networks: Benefits and Challenges. IEEE Wirel. Commun. 2009, 16, 88-96.
[52] Jelicic, V.; Magno, M.; Brunelli, D.; Bilas, V.; Benini, L. Benefits of Wake-up Radio in Energy-Efficient Multimodal Surveillance Wireless Sensor Network. IEEE Sens. J. 2014, 14, 3210-3220.
[53] Piyare, R.; Murphy, A.L.; Kiraly, C.; Tosato, P.; Brunelli, D. Ultra Low Power Wake-up Radios: A Hardware and Networking Survey. IEEE Commun. Surv. Tutor. 2017, 19, 2117-2157.

[54] Kumar, S.; Dalal, S.; Dixit, V. The OSI model: Overview on the seven layers of computer networks. Int. J. Comput. Sci. Inf. Technol. Res. 2014, 2, 461-466.

[55] Sadeghi, R.; Barraca, J.P.; Aguiar, R.L. A Survey on Cooperative MAC Protocols in IEEE 802.11 Wireless Networks. Wirel. Pers. Commun. 2016, 95, 1469-1493.

[56] Muzakkari, B.; Mohamed, M.A.; Mohamad, Z.; Jamil, N.; Abdul Kadir, M.F. Recent Advances in Energy Efficient-QoS Aware MAC Protocols for Wireless Sensor Network. Int. J. Adv. Comput. Res. 2018, 8, 212-228.

[57] Al-Janabi, T.A.; Al-Raweshidy, H.S. An Energy Efficient Hybrid MAC Protocol with Dynamic Sleep-Based Scheduling for High Density IoT Networks. IEEE Int. Things J. 2019, 6, 2273-2287.

[58] Gong, H.; Zhang, X.; Yu, L.; Wang, X.; Yi, F. A Study on MAC protocols for wireless sensor networks. In Proceedings of the 2009 Fourth International Conference on Frontier of Computer Science and Technology, Shanghai, China, 17-19 December 2009; pp. 728-732.

[59] Kaur, T.; Kumar, D. QoS Mechanisms for MAC Protocols in Wireless Sensor Networks: A Survey. IET Commun. 2019, 13, 2045-2062.

[60] Afroz, F.; Braun, R. Energy-Efficient MAC Protocols for Wireless Sensor Networks: A Survey. Int. J. Sens. Netw. 2020, 32, 150.

[61] Samara, G. Wireless sensor network MAC energy-efficiency protocols: A survey. In Proceedings of the 2020 21st International Arab Conference on Information Technology (ACIT), Giza, Egypt, 28-30 November 2020; pp. 1-5.

[62] Kandris, D.; Tsioumas, P.; Tzes, A.; Nikolakopoulos, G.; Vergados, D. Power Conservation through Energy Efficient Routing in Wireless Sensor Networks. Sensors 2009, 9, 7320-7342.

[63] Pantazis, N.A.; Nikolidakis, S.A.; Vergados, D.D. Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey. IEEE Commun. Surv. Tutor. 2013, 15, 551-591.

[64] Kandris, D.; Tsioumas, P.; Tzes, A.; Pantazis, N.; Vergados, D.D. Hierarchical energy efficient routing in wireless sensor networks. In Proceedings of the 16th IEEE Mediterranean Conference on Control and Automation (MED'08), Ajaccio, France, 25-27 June 2008; pp. 1856-1861.

[65] Nikolidakis, S.A.; Kandris, D.; Vergados, D.D.; Douligeris, C. Energy Efficient Routing in Wireless Sensor Networks through Balanced Clustering. Algorithms 2013, 6, 29-42.

[66] Chen, F.; Xu, Z.-L. Design and Manufacture of High-Performance Microbatteries: Lithium and Beyond. Microstructures 2022, 2, 2022012.

[67] Kyeremateng, N.A.; Hahn, R. Attainable Energy Density of Microbatteries. ACS Energy Lett. 2018, 3, 1172-1175.

[68] Toor, A.; Wen, A.; Maksimovic, F.; Gaikwad, A.M.; Pister, K.S.J.; Arias, A.C. Stencil-Printed Lithium-Ion Micro Batteries for IoT Applications. Nano Energy 2021, 82, 105666.

[69] Lyu, Z.; Lim, G.J.H.; Koh, J.J.; Li, Y.; Ma, Y.; Ding, J.; Wang, J.; Hu, Z.; Wang, J.; Chen, W.; et al. Design and Manufacture of 3D-Printed Batteries. Joule 2021, 5, 89-114.

[70] Patnaik, S.G.; Jadon, A.; Tran, C.C.H.; Estève, A.; Guay, D.; Pech, D. High Areal Capacity Porous Sn-Au Alloys with Long Cycle Life for Li-Ion Microbatteries. Sci. Rep. 2020, 10, 10405.

[71] Kurra, N.; Jenjeti, R.N. Micro-Electrochemical Capacitors: Progress and Future Status. J. Energy Storage 2022, 55, 105702.

[72] Shen, G. Printing flexible on-chip micro-supercapacitors. In Flexible Supercapacitors; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2022; pp. 261-282.

[73] Lethien, C.; Bideau, J.L.; Brousse, T. Challenges and Prospects of 3D Micro-Supercapacitors for Powering the Internet of Things. Energy Environ. Sci. 2019, 12, 96-115.

[74] Li, H.; Shen, H.; Shi, Y.; Wen, L.; Li, F. Progress and Prospects of Graphene for In-Plane Micro-Supercapacitors. New Carbon Mater. 2022, 37, 781-801.

[75] Liu, H.; Zhang, G.; Zheng, X.; Chen, F.; Duan, H. Emerging miniaturized energy storage devices for microsystem applications: From design to integration. Int. J. Extreme Manuf. 2020, 2, 042001.

[76] Ding, J.; Hu, W.; Paek, E.; Mitlin, D. Review of Hybrid Ion Capacitors: From Aqueous to Lithium to Sodium. Chem. Rev. 2018, 118, 6457-6498.

[77] Riaz, A.; Sarker, M.R.; Saad, M.H.M.; Mohamed, R. Review on Comparison of Different Energy Storage Technologies Used in Micro-Energy Harvesting, WSNs, Low-Cost Microelectronic Devices: Challenges and Recommendations. Sensors 2021, 21, 5041.

[78] Bu, F.; Zhou, W.; Xu, Y.; Du, Y.; Guan, C.; Huang, W. Recent Developments of Advanced Micro-Supercapacitors: Design, Fabrication and Applications. NPJ Flex. Electron. 2020, 4, 31.

[79] Guan, L.; Yu, L.; Chen, G.Z. Capacitive and Non-Capacitive Faradaic Charge Storage. Electrochim. Acta 2016, 206, 464-478.

[80] Yu, H.; Chin, K.-W. Learning Algorithms for Data Collection in RF-Charging IIoT Networks. IEEE Trans. Ind. Inform. 2022, 19, 88-97.

[81] Shi, Y.; Cui, X.; Qi, L.; Zhang, X.; Li, X.; Shen, H. A Novel Energy Harvesting Method for Online Monitoring Sensors in HVdc Overhead Line. IEEE Trans. Ind. Electron. 2022, 70, 2139-2143.

[82] Liu, Z.; Li, Y.; Yang, H.; Duan, N.; He, Z. An Accurate Model of Magnetic Energy Harvester in the Saturated Region for Harvesting Maximum Power: Analysis, Design, and Experimental Verification. IEEE Trans. Ind. Electron. 2022, 70, 276-285.

[83] Carlson, E.J.; Smith, J.R. A ±0.5-MV-Minimum-Input DC-DC Converter with Stepwise Adiabatic Gate-Drive and Efficient Timing Control for Thermoelectric Energy Harvesting. IEEE Trans. Circuits Syst. I Regul. Pap. 2022; preprint.

[84] Toledo, P.; Crovetti, P.; Aiello, O.; Alioto, M. Design of Digital OTAs with Operation down to 0.3v and NW Power for Direct Harvesting. IEEE Trans. Circuits Syst. I Regul. Pap. 2021, 68, 3693-3706.

[85] Zhou, S.; Lallart, M.; Erturk, A. Multistable Vibration Energy Harvesters: Principle, Progress, and Perspectives. J. Sound Vib. 2022, 528, 116886.

[86] Noh, Y.-S.; Seo, J.-I.; Kim, H.-S.; Lee, S.-G. A Reconfigurable DC-DC Converter for Maximum Thermoelectric Energy Harvesting in a Battery-Powered Duty-Cycling Wireless Sensor Node. IEEE J. Solid-State Circuits 2022, 57, 2719-2730.

[87] Liu, L.; Choi, S. Miniature Microbial Solar Cells to Power Wireless Sensor Networks. Biosens. Bioelectron. 2021, 177, 112970.

[88] Sarker, M.R.; Saad, M.H.M.; Olazagoitia, J.L.; Vinolas, J. Review of Power Converter Impact of Electromagnetic Energy Harvesting Circuits and Devices for Autonomous Sensor Applications. Electronics 2021, 10, 1108.

[89] Engmann, F.; Katsriku, F.A.; Abdulai, J.D.; Adu-Manu, K.S.; Banaseka, F.K. Low Power Energy Harvesting Systems: State of the Art and Future Challenges. Renew. Sustain. Energy Rev. 2021, 147, 111230.

[90] Morin, E.; Maman, M.; Guizzetti, R.; Duda, A. Comparison of the Device Lifetime in Wireless Networks for the Internet of Things. IEEE Access 2017, 5, 7097-7114.

[91] Khan, F.U.; Awais, M.; Rasheed, M.B.; Masood, B.; Ghadi, Y. A Comparison of Wireless Standards in IoT for Indoor Localization Using LoPy. IEEE Access 2021, 9, 65925-65933.
[92] Barker, P.; Hammoudeh, M. A Survey on low power network protocols for the Internet of things and wireless sensor networks. In Proceedings of the International Conference on Future Networks and Distributed Systems, Cambridge, UK, 19-20 July 2017.
[93] Mosin, S. A Model of LoRaWAN Communication in Class A for Design Automation of Wireless Sensor Networks Based on the IoT Paradigm.
[94] Lavric, A.; Popa, V. Performance Evaluation of LoRaWAN Communication Scalability in Large-Scale Wireless Sensor Networks. Wirel. Commun. Mob. Comput. 2018, 2018, 6730719.
[95] Abdallah, W.; Mnasri, S.; Nasri, N.; Val, T. Emergent IoT Wireless technologies beyond the year 2020: A comprehensive comparative analysis. In Proceedings of the 2020 International Conference on Computing and Information Technology (ICCIT-1441), Tabuk, Saudi Arabia, 9-10 September 2020; pp. 1-5.
[96] Schott, L.; Fromm, R.; Bouattour, G.; Kanoun, O.; Derbel, F. Analytical and Experimental Performance Analysis of Enhanced Wake-up Receivers Based on Low-Power Base-Band Amplifiers. Sensors 2022, 22, 2169.
[97] Galante-Sempere, D.; Ramos-Valido, D.; Khemchandani, S.L.; del Pino, J. Area-Efficient Integrated Current-Reuse Feedback Amplifier for Wake-up Receivers in Wireless Sensor Network Applications. Sensors 2022, 22, 1662.
[98] Nowbahari, A.; Marchetti, L.; Azadmehr, M. An oscillator-based wake-up receiver for wireless sensor networks. In Proceedings of the IEEE Sensors Applications Symposium (SAS), Sundsvall, Sweden, 23-25 August 2021; pp. 1-5.
[99] Mangal, V.; Kinget, P.R. A Wake-up Receiver with a Multi-Stage Self-Mixer and with Enhanced Sensitivity When Using an Interferer as Local Oscillator. IEEE J. Solid-State Circuits 2019, 54, 808-820.
[100] Hu, J.; Xu, G.; Hu, L.; Li, S.; Xing, Y. An Adaptive Energy Efficient MAC Protocol for RF Energy Harvesting WBANs. IEEE Trans. Commun. 2022, 2022, 1.
[101] Cotrim, R.S.; Caldeira, J.M.L.P.; Soares, V.N.G.J.; Azzoug, Y. Power Saving MAC Protocols in Wireless Sensor Networks: A Survey. TELKOMNIKA Telecommun. Comput. Electron. Control 2021, 19, 1778.
[102] Gambhir, S.; Fatima, N. Op-LEACH: An Optimized LEACH Method for Busty Traffic in WSNs. IEEE Xplore. https://doi.org/10.1109/ACCT.2014.94.
[103] Sendra, S.; Lloret, J.; Garcia, M.; Toledo, J. F. Power Saving and Energy Optimization Techniques for Wireless Sensor Neworks (Invited Paper). Journal of Communications 2011, 6 (6).
[104] Heinzelman, W. B.; Chandrakasan, A. P.; Balakrishnan, H. An Application-Specific Protocol Architecture for Wireless Microsensor Networks. IEEE Transactions on Wireless Communications 2002, 1 (4), 660-670. https://doi.org/10.1109/twc.2002.804190.
[105] Tong, M.; Tang, M. LEACH-B: An Improved LEACH Protocol for Wireless Sensor Network. IEEE Xplore. https://doi.org/10.1109/WICOM.2010.5601113.
[106] Tripathi, M.; Battula, R. B.; Gaur, M. S.; Laxmi, V. Energy Efficient Clustered Routing for Wireless Sensor Network. IEEE Xplore. https://doi.org/10.1109/MSN.2013.67.
[107] Liu, Y.; Xu, K.; Luo, Z.; Chen, L. A reliable clustering algorithm base on LEACH protocol in wireless mobile sensor networks. IEEE Xplore.
[108] Lei, Y.; Shang, F.; Long, Z.; Ren, Y. An Energy Efficient Multiple-Hop Routing Protocol for Wireless Sensor Networks. IEEE Xplore. https://doi.org/10.1109/ICINIS.2008.69.

[109] Loscri, V.; Morabito, G.; Marano A., "A two-levels hierarchy for low-energy adaptive clustering hierarchy (TL-LEACH)," in Proc. IEEE 62nd Vehicular Technology Conference, pp. 1809-1813, 2005.

[110] Singh, S. K.; Kumar, P.; Singh, J. P. A Survey on Successors of LEACH Protocol. IEEE Access 2017, 5, 4298-4328. https://doi.org/10.1109/access.2017.2666082.

[111] Jerbi, W.; Guermazi, A.; Trabelsi, H. O-LEACH of Routing Protocol for Wireless Sensor Networks. IEEE Xplore.

[112] Ren, P.; Qian, J.; Li, L.; Zhao, Z.; Li, X. Unequal Clustering Scheme Based LEACH for Wireless Sensor Networks. IEEE Xplore.

[113] Sasikala, A.; Sangameswaran, N; Aravindh, P.; "Improving the energy efficiency of LEACH protocol using VCH in wireless sensor network," Int. J. Eng. Develop. Res., vol. 3, (2), 2015, 918-924.

[114] Lee, J.-Y.; Jung, K.-D.; Moon, S.-J.; Jeong, H.-Y. Improvement on LEACH Protocol of a Wide-Area Wireless Sensor Network. Multimedia Tools and Applications 2016, 76 (19), 19843-19860.

[115] Farooq, M. O.; Dogar, A. B.; Shah, G. A. MR-LEACH: Multi-hop Routing with Low Energy Adaptive Clustering Hierarchy. IEEE Xplore.

[116] Hong, J.; Kook, J.; Lee, S.-J.; Kwon, D.; Yi, S. T-LEACH: The Method of Threshold-Based Cluster Head Replacement for Wireless Sensor Networks. Information Systems Frontiers 2009, 11 (5), 513-521. https://doi.org/10.1007/s10796-008-9121-4.

[117] Yektaparast, A.; Nabavi, F.-H.; Sarmast, A. An improvement on LEACH protocol (Cell-LEACH). IEEE Xplore. https://ieeexplore.ieee.org/abstract/document/6174834.

[118] Omari, M.; Fateh, W. H. Enhancing multihop routing protocols in wireless sensor networks using LEACH-1R. IEEE Xplore.

[119] Voigt, T.; Dunkels, A.; Alonso, J.; Ritter, H.; Schiller, J. Solar-aware clustering in wireless sensor networks. IEEE Xplore.

[120] Yueyun, C.; Yue-Long, Z.; Jianwei, A.; Qian, L. An Energy-Saving Routing Protocol Based on LEACH. IEEE Xplore.

[121] Tang, C.; Tan, Q.; Han, Y.; An, W.; Li, H.; Tang, H. "An energy harvesting aware routing algorithm for hierarchical clustering wireless sensor networks," KSII Transactions on Internet and Information Systems (TIIS), vol. 10, (2), 2016 pp. 504-521.

[122] Adrian Ribeiro Ferreira; Marcos Vinicios Vilaça; Oliveira, L.; Habib, E.; Hao Chi Wong; Antonio. On the Security of Cluster-Based Communication Protocols for Wireless Sensor Networks. Lecture Notes in Computer Science 2005, 449-458.

[123] Kim, D.S.; Chung, Y.-J. Self-Organization Routing Protocol Supporting Mobile Nodes for Wireless Sensor Network. IEEE Xplore.

[124] Saminathan, A.G.; Karthik, S.; Post, S. "DAO-LEACH: An approach for energy efficient routing based on data aggregation and optimal clustering in wsn," Life Science Journal, vol. 10, (7), 2013.

[125] Varga, A.; Hornig, R. An overview of the OMNeT++ simulation environment. Proceedings of the First International ICST Conference on Simulation Tools and Techniques for Communications Networks and Systems 2008.

[126] Kurkowski, S.; Camp, T.; Mushell, N.; Colagrosso, M. A visualization and analysis tool for NS-2 wireless simulations: iNSpect. IEEE Xplore.

[127] Khan, M. Z.; Askwith, B.; Bouhafs, F.; Asim, M. Limitations of Simulation Tools for Large-Scale Wireless Sensor Networks. IEEE Xplore.

[128] Campanile, L.; Gribaudo, M.; Iacono, M.; Marulli, F.; Mastroianni, M. Computer Network Simulation with ns-3: A Systematic Literature Review. Electronics 2020, 9, 272.

[129] Nayyar, A.; Singh, A. "A comprehensive review of simulation tools for wireless sensor networks (WSNs)," Journal of Wireless Networking and Communications, vol. 5, no. 1, pp. 19-47, 2015.
[130] Chang, X. Network Simulations with OPNET. Winter Simulation Conference 1999.
[131] Evangelakos, E.A.; Kandris, D.; Rountos, D.; Tselikis, G.; Anastasiadis, E. Energy Sustainability in Wireless Sensor Networks: An Analytical Survey. J. Low Power Electron. Appl. 2022, 12, 65. https://doi.org/10.3390/jlpea12040065.
[132] Rountos, D.; Kandris, D.; Evangelakos, E.A.; Tselikis, G. Energy Efficient Routing in Wireless Sensor Networks: A Comparative Study on LEACH Protocol and its Successors. IEEE Xplore. https://doi.org/10.1109/PACET56979.2022.9976317.
[133] Kandris, D.; Evangelakos, E.A.; Rountos, D.; Tselikis, G.; Anastasiadis, E. LEACH-Based Hierarchical Energy Efficient Routing in Wireless Sensor Networks AEU - International Journal of Electronics and Communications, Volume 169, 2023, 154758, ISSN 1434-8411, https://doi.org/10.1016/j.aeue.2023.154758
[134] Sharma, D.; Ojha, A.; Bhondekar, A.P. Heterogeneity Consideration in Wireless Sensor Networks Routing Algorithms: A Review. J. Supercomput. 2018, 75, 2341-2394.
[135] Verma, S.; Sood, N.; Sharma, A.K. A novelistic approach for energy efficient routing using single and multiple data sinks in heterogeneous wireless sensor network. Peer Netw. Appl. 2019, 12, 1110-1136.
[136] Gupta, P.; Tripathi, S.; Singh, S. Energy Efficient Rendezvous Points Based Routing Technique Using Multiple Mobile Sink in Heterogeneous Wireless Sensor Networks. Wirel. Netw. 2021, 27, 3733-3746.
[137] Agbehadji, I.E.; Millham, R.C.; Abayomi, A.; Jung, J.J.; Fong, S.J.; Frimpong, S.O. Clustering Algorithm Based on Nature-Inspired Approach for Energy Optimization in Heterogeneous Wireless Sensor Network. Appl. Soft Comput. 2021, 104, 107171.
[138] Getahun, M.; Azath, M.; Sharma, D.P.; Tuni, A.; Adane, A. Efficient Energy Utilization Algorithm through Energy Harvesting for Heterogeneous Clustered Wireless Sensor Network. Wirel. Commun. Mob. Comput. 2022, 2022, 4154742.
[139] Dudeja, D.; Hera, S.Y.; Doohan, N.V.; Dubey, N.; Mahaveerakannan, R.; Ahanger, T.A.; Hinga, S.K. Energy Efficient and Secure Information Dissemination in Heterogeneous Wireless Sensor Networks Using Machine Learning Techniques. Wirel. Commun. Mob. Comput. 2022, 2022, e2206530.
[140] Yue, Y.-G.; He, P. A Comprehensive Survey on the Reliability of Mobile Wireless Sensor Networks: Taxonomy, Challenges, and Future Directions. Inf. Fusion 2018, 44, 188-204.
[141] Zafar, S.; Bashir, A.; Chaudhry, S.A. Mobility-Aware Hierarchical Clustering in Mobile Wireless Sensor Networks. IEEE Access 2019, 7, 20394-20403.
[142] Hao, S.; Zhang, H.; Wang, J. A Learning Automata Based Stable and Energy-Efficient Routing Algorithm for Discrete Energy Harvesting Mobile Wireless Sensor Network. Wirel. Pers. Commun. 2019, 107, 437-469.
[143] Gupta, N.K.; Yadav, R.S.; Nagaria, R.K. 3D Geographical Routing Protocols in Wireless Ad Hoc and Sensor Networks: An Overview. Wirel. Netw. 2019, 26, 2549-2566.
[144] Kumari, J.; Kumar, P.; Singh, S.K. Localization in Three-Dimensional Wireless Sensor Networks: A Survey. J. Supercomput. 2019, 75, 5040-5083.
[145] Hussein, W.A.; Ali, B.M.; Rasid, M.; Hashim, F. Smart Geographical Routing Protocol Achieving High QoS and Energy Efficiency Based for Wireless Multimedia Sensor Networks. Egypt. Inform. J. 2022, 23, 225-238.

[146] Li, S.; Kim, J.G.; Han, D.H.; Lee, K.S. A Survey of Energy-Efficient Communication Protocols with QoS Guarantees in Wireless Multimedia Sensor Networks. Sensors 2019, 19,199.
[147] Kandris, D.; Tsagkaropoulos, M.; Politis, I.; Tzes, A.; Kotsopoulos, S. A hybrid scheme for video transmission over wireless multimedia sensor networks. In Proceedings of the IEEE 17th Mediterranean Conference on Control and Automation, Thessaloniki, Greece, 24-26 June 2009; pp. 964-969.
[148] Nikolakopoulos, G.; Kandris, D.; Tzes, A. Adaptive compression of slowly varying images transmitted over wireless sensor networks. Sensors 2010, 10, 7170-7191.
[149] Nikolakopoulos, G.; Stavrou, P.; Tsitsipis, D.; Kandris, D.; Tzes, A.; Theocharis, T. A dual scheme for compression and restoration of sequentially transmitted images over Wireless Sensor Networks. Ad Hoc Netw. 2013, 11, 410-426.
[150] Matheen, M.A.; Sundar, S. IoT Multimedia Sensors for Energy Efficiency and Security: A Review of QoS Aware and Methods in Wireless Multimedia Sensor Networks. Int. J. Wirel. Inf. Netw. 2022, 29, 407-418.
[151] Tekin, N.; Gungor, V.C. Analysis of Compressive Sensing and Energy Harvesting for Wireless Multimedia Sensor Networks. Ad Hoc Netw. 2020, 103, 102164.
[152] Manman, L.; Goswami, P.; Mukherjee, P.; Mukherjee, A.; Yang, L.; Ghosh, U.; Menon, V.G.; Qi, Y.; Nkenyereye, L. Distributed Artificial Intelligence Empowered Sustainable Cognitive Radio Sensor Networks: A Smart City On-Demand Perspective. Sustain. Cities Soc. 2021, 75, 103265.
[153] Sharma, H.; Haque, A.; Blaabjerg, F. Machine Learning in Wireless Sensor Networks for Smart Cities: A Survey. Electronics 2021, 10, 1012.
[154] Kumar, M.; Mukherjee, P.; Verma, K.; Verma, S.; Rawat, D.B. Improved Deep Convolutional Neural Network Based Malicious Node Detection and Energy-Efficient Data Transmission in Wireless Sensor Networks. IEEE Trans. Netw. Sci. Eng. 2022, 9, 3272-3281.
[155] Lipare, A.; Edla, D.R.; Dharavath, R. Fuzzy Rule Generation Using Modified PSO for Clustering in Wireless Sensor Networks. IEEE Trans. Green Commun. Netw. 2021, 5, 846-857.
[156] Sert, S.A.; Yazici, A. Increasing Energy Efficiency of Rule-Based Fuzzy Clustering Algorithms Using CLONALG-M for Wireless Sensor Networks. Appl. Soft Comput. 2021, 109, 107510.
[157] Osamy, W.; Khedr, A.M.; Salim, A.; Al Ali, A.I.; El-Sawy, A.A. Recent Studies Utilizing Artificial Intelligence Techniques for Solving Data Collection, Aggregation and Dissemination Challenges in Wireless Sensor Networks: A Review. Electronics 2022, 11, 313.
[158] Ajmi, N.; Helali, A.; Lorenz, P.; Mghaieth, R. MWCSGA-Multi Weight Chicken Swarm Based Genetic Algorithm for Energy Efficient Clustered Wireless Sensor Network. Sensors 2021, 21, 791.
[159] Wang, S. Multipath Routing Based on Genetic Algorithm in Wireless Sensor Networks. Math. Probl. Eng. 2021, 2021, e4815711.
[160] Yadav, R.; Sreedevi, I.; Gupta, D. Bio-Inspired Hybrid Optimization Algorithms for Energy Efficient Wireless Sensor Networks: A Comprehensive Review. Electronics 2022, 11, 1545.
[161] Chen, H.-W.; Liang, C.-K. Genetic Algorithm versus Discrete Particle Swarm Optimization Algorithm for Energy-Efficient Moving Object Coverage Using Mobile Sensors. Appl. Sci. 2022, 12, 3340.

[162] Ahmed, N.; Kanhere, S.S.; Jha, S. On the Importance of Link Characterization for Aerial Wireless Sensor Networks. IEEE Commun. Mag. 2016, 54, 52-57.
[163] Kisseleff, S.; Akyildiz, I.F.; Gerstacker, W.H. Survey on Advances in Magnetic Induction-Based Wireless Underground Sensor Networks. IEEE Int. Things J. 2018, 5, 4843-4856.
[164] Banaseka, F.K.; Katsriku, F.; Abdulai, J.D.; Adu-Manu, K.S.; Engmann, F.N.A. Signal Propagation Models in Soil Medium for the Study of Wireless Underground Sensor Networks: A Review of Current Trends. Wirel. Commun. Mob. Comput. 2021, 2021, 8836426.
[165] Luo, J.; Chen, Y.; Wu, M.; Yang, Y. A Survey of Routing Protocols for Underwater Wireless Sensor Networks. IEEE Commun. Surv. Tutor. 2021, 23, 137-160.
[166] Subramani, N.; Mohan, P.; Alotaibi, Y.; Alghamdi, S.; Khalaf, O.I. An Efficient Metaheuristic-Based Clustering with Routing Protocol for Underwater Wireless Sensor Networks. Sensors 2022, 22, 415.
[167] Sachan, S.; Sharma, R.; Sehgal, A. Energy Efficient Scheme for Better Connectivity in Sustainable Mobile Wireless Sensor Networks. Sustain. Comput. Inform. Syst. 2021, 30, 100504.
[168] Kumar, S.; Duttagupta, S.; Rangan, V.P.; Ramesh, M.V. Reliable Network Connectivity in Wireless Sensor Networks for Remote Monitoring of Landslides. Wirel. Netw. 2019, 26, 2137-2152.
[169] Sharma, A.; Chauhan, S. A Distributed Reinforcement Learning Based Sensor Node Scheduling Algorithm for Coverage and Connectivity Maintenance in Wireless Sensor Network. Wirel. Netw. 2020, 26, 4411-4429.
[170] Tarnaris, K.; Preka, I.; Kandris, D.; Alexandridis, A. Coverage and K-Coverage Optimization in Wireless Sensor Networks Using Computational Intelligence Methods: A Comparative Study. Electronics 2020, 9, 675.
[171] Cao, L.; Yue, Y.; Cai, Y.; Zhang, Y. A Novel Coverage Optimization Strategy for Heterogeneous Wireless Sensor Networks Based on Connectivity and Reliability. IEEE Access 2021, 9, 18424-18442.
[172] Kandris, D.; Vergados, D.J.; Vergados, D.D.; Tzes, A. A routing scheme for congestion avoidance in wireless sensor networks. In Proceedings of the 6th Annual IEEE Conference on Automation Science and Engineering (CASE 2010), Toronto, ON, Canada, 21-24 August 2010; pp. 21-24.
[173] Kandris, D.; Tselikis, G.; Anastasiadis, E.; Panaousis, E.; Dagiuklas, T. COALA: A protocol for the avoidance and alleviation of congestion in wireless sensor networks. Sensors 2017, 17, 2502.
[174] Ploumis, S.E.; Sgora, A.; Kandris, D.; Vergados, D.D. Congestion avoidance in wireless sensor networks: A survey. In Proceedings of the 2012 IEEE Panhellenic Conference on Informatics (PCI 2012), Piraeus, Greece, 5-7 October 2012; pp. 234-239.
[175] Bohloulzadeh, A.; Rajaei, M. A Survey on Congestion Control Protocols in Wireless Sensor Networks. Int. J. Wirel. Inf. Netw. 2020, 27, pp. 365-384.
[176] Kaur, T.; Kumar, D. A Survey on QoS Mechanisms in WSN for Computational Intelligence Based Routing Protocols. Wirel. Netw. 2019, 26, 2465-2486.
[177] Sakthidasan @ Sankaran, K.; Gao, X.-Z.; Devabalaji, K.R.; Mohana Roopa, Y. Energy Based Random Repeat Trust Computation Approach and Reliable Fuzzy and Heuristic Ant Colony Mechanism for Improving QoS in WSN. Energy Rep. 2021, 7, 7967-7976.
[178] Selvi, M.; Thangaramya, K.; Ganapathy, S.; Kulothungan, K.; Khannah Nehemiah, H.; Kannan, A. An Energy Aware Trust Based Secure Routing Algorithm for Effective

Communication in Wireless Sensor Networks. Wirel. Pers. Commun. 2019, 105, 1475-1490.

[179] Haseeb, K.; Almogren, A.; Islam, N.; Ud Din, I.; Jan, Z. An Energy-Efficient and Secure Routing Protocol for Intrusion Avoidance in IoT-Based WSN. Energies 2019, 12, 4174.

[180] Shahid, H.; Ashraf, H.; Javed, H.; Humayun, M.; Jhanjhi, N.; AlZain, M.A. Energy Optimised Security against Wormhole Attack in IoT-Based Wireless Sensor Networks. Comput. Mater. Contin. 2021, 68, 1967-1981.

[181] Kandris, D.; Alexandridis, A.; Dagiuklas, T.; Panaousis, E.; Vergados, D.D. Multiobjective Optimization Algorithms for Wireless Sensor Networks. Wirel. Commun. Mob. Comput. 2020, 2020, 4652801.

[182] Singh, O.; Rishiwal, V.; Chaudhry, R.; Yadav, M. Multi-Objective Optimization in WSN: Opportunities and Challenges. Wirel. Pers. Commun. 2021, 121, 127-152.