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Review

Energy Sustainability in Wireless Sensor Networks: An Analytical Survey

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Abstract: Wireless Sensor Networks (WSNs) are considered to be among the most important scientific domains. Yet, the exploitation of WSNs suffers from the severe energy restrictions of their electronic components. For this reason there are numerous scientific methods that have been proposed aiming to achieve the extension of the lifetime of WSNs, either by energy saving or energy harvesting or through energy transfer. This study aims to analytically examine all of the existing hardware-based and algorithm-based mechanisms of this kind. The operating principles of 48 approaches are studied, their relative advantages and weaknesses are highlighted, open research issues are discussed, and resultant concluding remarks are drawn.

Keywords: wireless sensor networks; energy sustainability; energy efficiency; energy saving; energy harvesting; energy conservation; energy transfer; review

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1. Introduction

A 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.

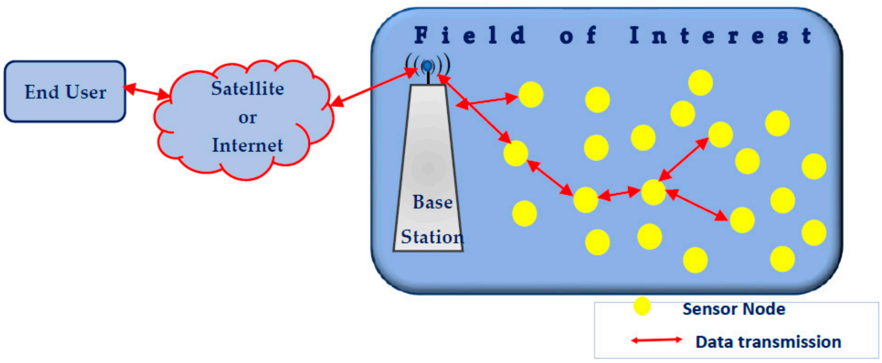

Figure 1. Typical architecture of a wireless sensor network.

WSNs, due to the collaboration of their sensor nodes and their BSs, are able to monitor the current conditions at widespread FoIs. This makes WSNs be ideal to support a constantly increasing range of human activities [4]. Specifically, although the first WSNs ever used served only military purposes [5], nowadays WSNs are not only still used in the military sector [6] but they also are utilized in an extensive variety of civil applications. Environmental and habitat monitoring, energy management, object tracking, fire detection, machine failure diagnosis and various other industrial applications, health and biomedical applications, agriculture, livestock farming, inventory control, traffic control, smart homes, smart cities, surveillance and reconnaissance are some of the domains in which WSNs are utilized [7–17].

Yet, despite the evident advantages that WSNs offer, 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 [18]. 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 [19–25]. In this research work, as illustrated in Figure 2, energy sustainability methods are classified into two main categories, i.e., the hardware-based methods and the algorithm-based methods.

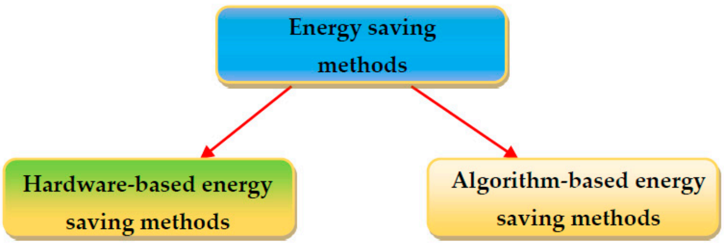

Figure 2. Categorization of energy sustainability mechanisms.

In accordance with the above, the remainder of this article identifies the causes of energy consumption in WSNs and analyzes all (i.e., 48) mechanisms that have been proposed in order to reduce this energy consumption and consequently extend the lifetime of nodes in WSNs. Specifically, in Section 2 the causes of energy consumption and waste in WSNs are analyzed. Section 3 describes the architecture of sensor nodes and analyzes the existing hardware-based mechanisms for energy sustainability in WSNs, via energy saving, energy harvesting, and wireless energy transfer. Section 4 describes the protocol stack of sensor nodes, presents the communication technologies used in WSNs and analyzes all algorithm-based mechanisms that have been proposed for energy sustainability in WSNs. In Section 5, the main findings of this survey along with open research issues are discussed. Finally, in Section 6, the corresponding concluding remarks that are extracted from this research work are resumed.

2. 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 [20]:

- 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.

3. Hardware-Based Energy Sustainability in WSNs

3.1. The Architecture of Wireless Sensor Nodes

Each sensor node of a WSN is a Micro Electromechanical system (MEMS) [1,26], which is composed of four main and two optional subsystems, as illustrated in Figure 3. 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 the communication through optical, or infrared signals may be used.

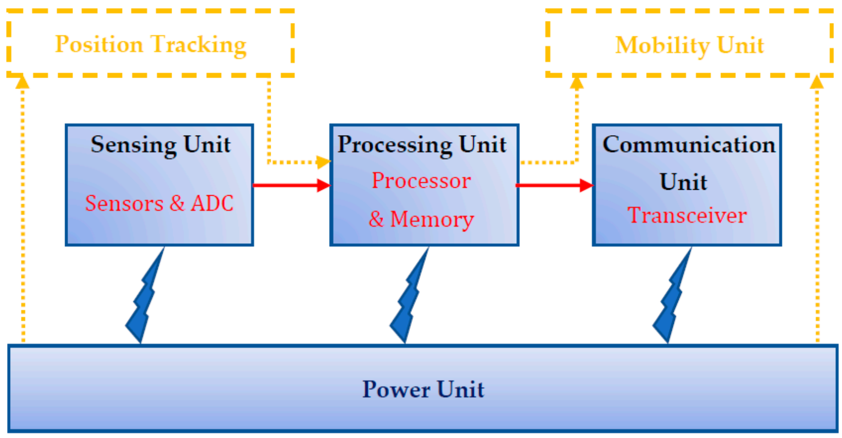

Figure 3. Typical architecture of a wireless sensor node.

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.

3.2. Hardware-Based Methods for Energy Sustainability

As illustrated in Figure 4, 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 [19–25].

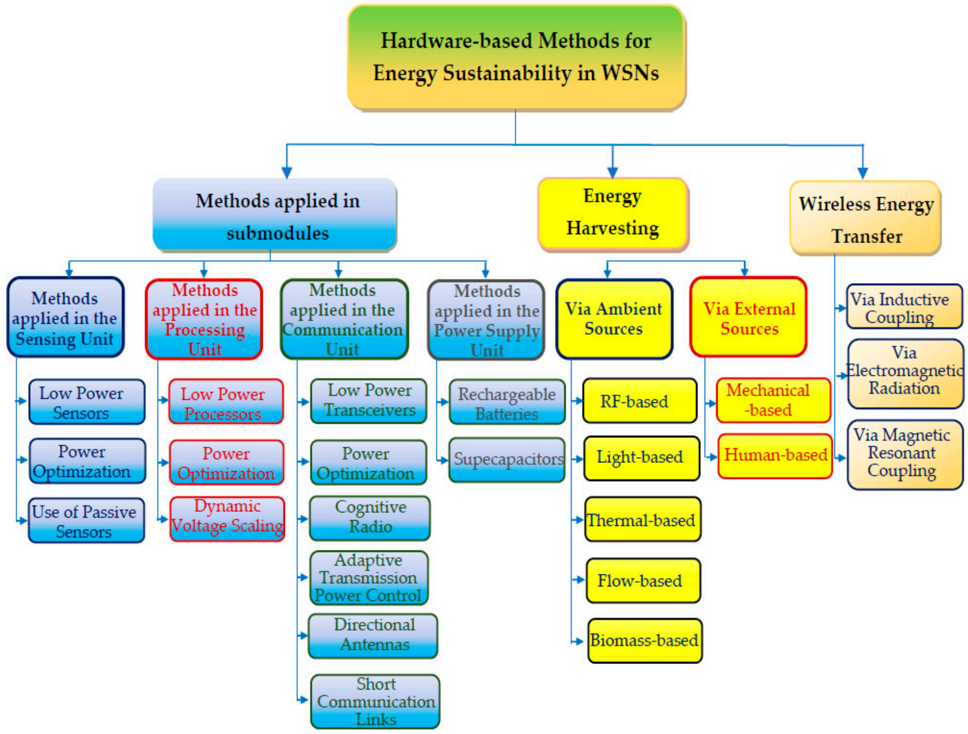

Figure 4. Categorization of hardware-based methods for energy sustainability in WSNs.

3.2.1. 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 [1–3,26]. 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 in order 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 [21,24].
    - ○ 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 [27].
- The design of the central Processing Unit is related to the choice of the optimum microprocessors and microcontrollers (MCUs) [19,21].
    - ○ 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 [28,29]. 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 unit of 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 [19];
  - ○ 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 a network energy conservation [21]. 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 [19]. Additionally, the power levels of the transmitter are adjusted according to the needs of each application, in order to limit the energy consumption [24];
  - ○ 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 [21];
  - ○ 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 [21].
- Regarding the power supply unit of sensor nodes, small batteries with restricted capacity [22] 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 [19]. In the cases

where battery recharge is difficult to perform, techniques that aim at either estimating [30] or prolonging [31] 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 [19].

3.2.2. 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 [32,33]. 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 [19,34]. The overall energy harvesting process is illustrated in Figure 5.

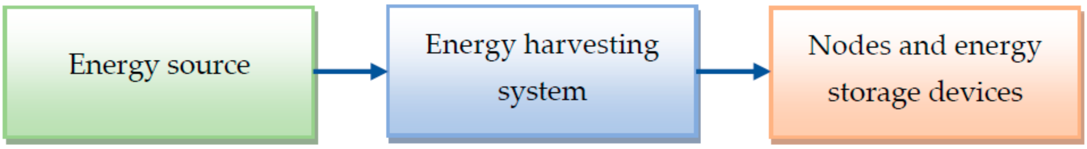

Figure 5. Overview of energy harvesting process.

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 [35,36].

- 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 [33,34].
   - 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 [35,37].
   - 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 [38,39];
   - 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 [33,34,36];

    - ○ 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 [33];
    - ○ 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 [33,35].

- 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 [33,36];
    - ○ 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 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 [34,39,40].

3.2.3. 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 [19]. 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 [41]. 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 [42]. 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 in close distance. The amount of generated energy is proportional to the size of the coil. This method is simple and safe to apply [19];
- 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 [42]. 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 (EM) 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 [43].

4. 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.

4.1. Protocol Stack of Sensor Nodes and BSs

The operation of both every sensor node and the base station is managed by the so called protocol stack that, as illustrated in Figure 6, consists of five layers, i.e.: the application layer, the transport layer, the network layer, the data link layer, and the physical layer [1,3,44].

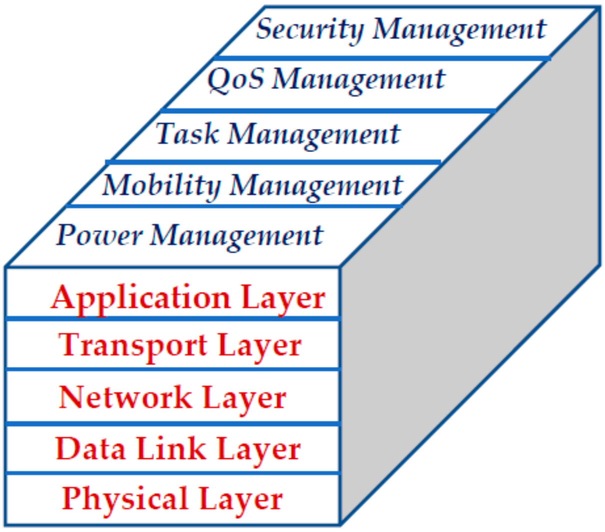

Figure 6. Protocol stack of a wireless node.

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, and the 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 [44]. 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.

4.2. 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 [45].

For instance, the transmission range is a metric used in order to categorize such technologies as either short-range (with coverage $\leq$ 10 m), medium-range (with coverage 10–100 m), or long-range (with coverage $\geq$ 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 [46]. 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 [47]. 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 [48–50].

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.

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

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

4.3. 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 7, algorithm-based mechanisms may be classified into three main categories, i.e., data driven, duty cycling, and energy efficient routing, along with various subcategories [20,21,23,51]. They are all described in what follows in the rest of this section.

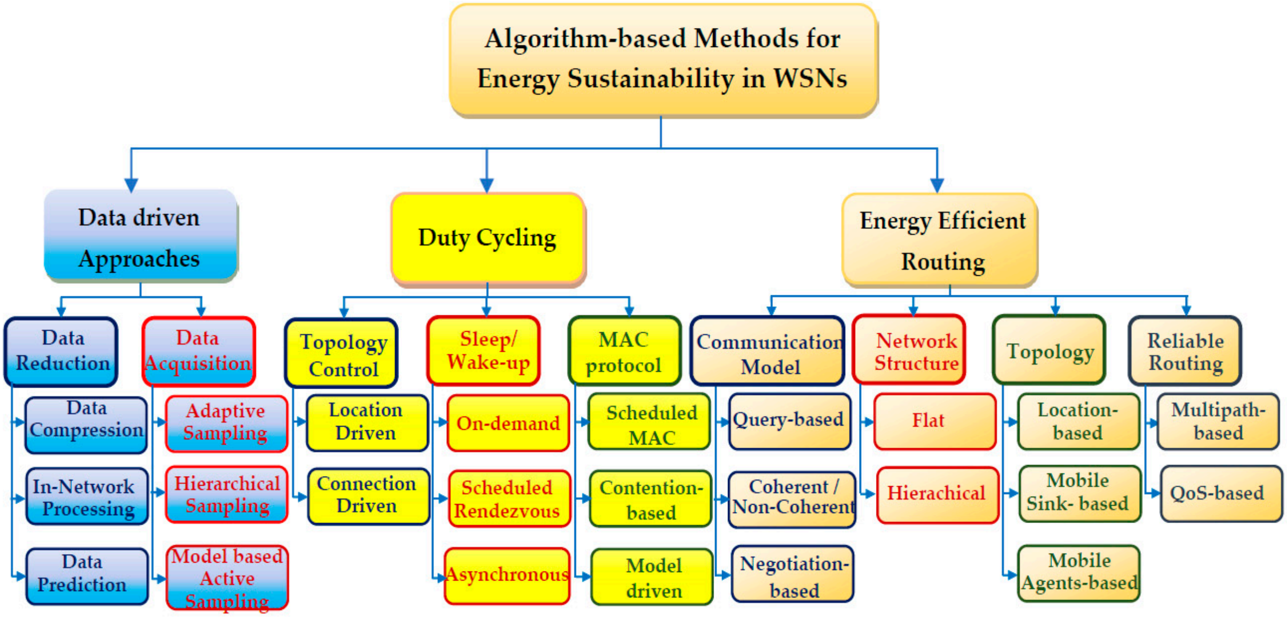

Figure 7. Categorization of algorithm-based energy-saving mechanisms in WSNs.

4.3.1. 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 [52]. 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 in order to avoid the creation of redundant samples, or by reducing the mandatory sensing tasks [21]. 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 [21];
    - ○ 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 [53];
    - ○ 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 num-

ber of the unnecessary transmissions and subsequently the corresponding expenditure [23,54].

- 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 [55]. 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 [56];
  - 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 [57];
  - 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. [37,58].

4.3.2. 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 [59]. It is implemented by using appropriate wake-up oscillators that perform clock generation [60,61] and wake-up receivers that perform the idle listening while keeping the main radio completely off [62–64]. 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 [19]. 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 [23].

    - 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 in order 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 [23].
    - 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 [19]. 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 [23];
    - 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 [20];
    - 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 [20,23].
- 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 [65,66]. To communicate with each other, sensor nodes utilize a shared medium. In the case of WSNs, the medium is the radio channel [67,68]. 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 [69,70].

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 [71,72]. MAC protocols are classified in three main categories: scheduled, contention-based and hybrid [67].

- 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 [23].

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 [68].

- ○ 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 [68]. 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 [67,68].

4.3.3. Energy Efficient Routing

By default, the transmission and routing of data in WSNs consume great amounts of the energy that sensor nodes retain [73]. 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 [51,74].

- 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 [51];
    - ○ 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 [74];

    - 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 with all of the rest network nodes. Protocols of this kind perform well in networks constituted from a small quantity of sensor nodes [51];
    - 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 [75]. In this way, data aggregation is enabled, and great scalability is achieved. Additionally, load balancing is achieved [76].
- 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 [74];
    - 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 [51];
    - 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 [51].
- 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 [74];
    - 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 [51].

5. Discussion

In the previous sections 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.

5.1. Challenges and Open Research Issues in Hardware-Based Methods

Regarding the submodules of sensor nodes, as aforementioned, the use of low-power electronic components is necessitated [19,21,24]. 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 [19,23]. Moreover, Passive Sensors cannot be used in all types of applications [27]. The method of Dynamic Voltage Scaling that is applied in the processing unit of nodes, is effective only when sensing requests are less frequent [28,29]. 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 [21]. The increase of latency and the modification of routing paths are the main weaknesses of Adaptive Power Transmission [19,24]. In many cases, the use of Directional Antennas is not feasible if localization methods are not applied in order to assist orientation procedures [21]. 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 [21]. 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 [19,22].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 [77–81]. 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 [82–85]. 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 [86–90].

Energy Harvesting, as aforementioned, can substantially upgrade the energy sustainability in WSNs [33]. Thus, novel research is necessitated not only for the development of advanced equipment such as low energy harvesters, converters, and energy storage systems (ESS) [91–98], 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 [99,100]. Furthermore, health limitations associated with RF power obstruct the wide use of RF-based energy harvesting. Moreover, ambient RF is neither predictable nor controllable [35]. 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 day time as long as the weather conditions are adequately good [38,39]. Thermal-based energy harvesting not only is unpredictable and uncontrollable when caused by temperature variations but also has low efficiency [36]. Flow-based energy harvesting is not only unpredictable but also uncontrollable [35]. 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 [33].

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 [19]. 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 [41]. 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 [42]. In wireless energy transfer via Electromagnetic Radiation, line of sight is essential and the presence of radiation triggers various health and safety concerns [43].

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.

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

Method	Basic Operation	Advantages	Disadvantages
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.

5.2. Challenges and Open Research Issues in Algorithm-Based Methods

In this section, the challenges that raise from the inherent weaknesses of the algorithm-based methods are discussed.

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 [101–106].

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 [21]. In-Network Processing is associated with non-negligible energy consumption [47]. 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 [23,54]. Regarding Data Acquisition methods, Adaptive Sampling is characterized by high complexity and high computational overhead, thus necessitating central control [56]. 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 [57]. In Model-based Active Sampling mechanisms complex computations are needed, thus increasing processing load [58].

In Duty Cycling methods, the use of specialized modules is necessary [107–110]. 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 fulfil. Additionally, if GPS modules are used to overcome this problem, such modules not only are costly but also cause interference to network communications [19,23]. 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 [20,23]. 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) [67]. 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 [68]. Thus novel research must be carried out [111,112].

Finally, as already mentioned, Energy Efficient Protocols may be classified according to Communication Model, Network Structure, Topology, and Reliable Routing [51,74]. 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 [51]. 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 [51]. 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 [74]. 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 [51].

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.

5.3. General Challenges and Open Research Issues

Following the aforementioned discussion 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 too common to overlook. This issue has to be handled by novel research works [113–118].

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

Method	Basic Operation	Advantages	Disadvantages
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 are needed.
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 routes are used. Latency is reduced.	High overhead. Limited scalability. GPS units are costly and 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.

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 [119–121].

In Furthermore, the majority of methods for energy sustainability consider two dimensional networks. Hence, more research works should be conducted regarding three dimensional WSNs [122,123].

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 [124–130].

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 [19]. Likewise, there is lack of specialized equipment for wireless energy transfer in corresponding emulation tests performed using testbeds, due to its high cost [19]. 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 [131–140].

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 [141–145].

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 [146,147].

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 [148–150].

Additionally, congestion avoidance and congestion control [151–154] 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 [155,156].

Furthermore, security schemes for WSNs to assure confidentiality, authentication, integrity, availability, and freshness are required [157–159].

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 [160,161] have to be developed.

6. 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 article, 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.

For these reasons, the authors of this research work believe that the achievement of energy sustainability in WSNs will keep on attracting scientific awareness and hope that this survey will be helpful to the scientists that apply their research efforts at this very exciting domain.

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