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Comparative Study of Energy Efficient Routing Techniques in Wireless Sensor Networks

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Abstract: This paper surveys the energy-efficient routing protocols in wireless sensor networks (WSNs). It provides a classification and comparison following a new proposed taxonomy distinguishing nine categories of protocols, namely: Latency-aware and energy-efficient routing, next-hop selection, network architecture, initiator of communication, network topology, protocol operation, delivery mode, path establishment and application type. We analyze each class, discuss its representative routing protocols (mechanisms, advantages, disadvantages . . .) and compare them based on different parameters under the appropriate class. Simulation results of LEACH, Mod-LEACH, iLEACH, E-DEEC, multichain-PEGASIS and M-GEAR protocols, conducted under the NS3 simulator, show that the routing task must be based on various intelligent techniques to enhance the network lifespan and guarantee better coverage of the sensing area.

Keywords: wireless sensor networks; routing protocols; performance analysis; taxonomy; classification

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Citation: Zagrouba, R.; Kardi, A. Comparative Study of Energy Efficient Routing Techniques in Wireless Sensor Networks. *Information* **2021**, *12*, 42. https://doi.org/10.3390/info12010042

Received: 19 November 2020
Accepted: 21 December 2020
Published: 18 January 2021

1. Introduction

Enabled by advances in intelligent systems, distributed signal processing and wireless communication technologies, and motivated by military and civil applications, WSNs recognized a new generation of a multi-functional sensor able to capture various types of environmental and physical conditions and characterized by their low battery, low data processing capacity, small size and ability to move around and organize themselves into a network [1–3].

These limited characteristics bring the necessity to achieve efficient management of the routing task in order to the increase the network lifespan [4]. Thereby, much recent research in this field aims to implement highly efficient routing protocols that will be able to overcome the severe resource constraints of sensors [5,6].

Many protocols have been designed for WSNs according to the diverse requirements of applications and the multitude of WSNs characteristics [7–9].

Several surveys that have sought to analyze and classify these routing protocols according to different parameters have been published. The aim of our work is to provide a survey of these protocols following a new classification model presented in previous work. We classify the mainstream recent proposed protocols using our taxonomy, distinguishing nine categories of protocols: latency-aware and energy-efficient routing, next-hop selection, network architecture, initiator of communication, network topology, protocol operation, delivery mode, path establishment and application type. Under all categories, we present a classification and comparison of recent routing techniques and bring out their advantages and disadvantages.

In the following, we review some previous surveys in Section 2, then we present our proposed classification model and discuss the recent routing protocols in Section 3.

A performance evaluation through the NS3 simulator is discussed in Section 4. Lastly, the conclusion and our future work are presented in Section 5.

2. Previous Surveys of WSNs Routing Protocols

Many surveys of routing protocols have been presented in recent years [10,11]. They present some taxonomy of routing protocols in WSNs according to some characters of the most popular protocols. Table 1 summarizes the main contributions of these surveys. The next section presents our proposed taxonomy.

Table 1. Surveys of wireless sensor networks (WSNs) routing protocols.

Year	Surveys	Defined Routing Protocols Classes															
		Flat-Based	Location-Based	Hierarchical	Data-Centric	Multipath	Network Structure	Protocol Operation	Routing Objectives	Architecture-Based (Topology)	Power Transmission	Route Selection-Based	QoS-Based	Mobility-Based	Heterogeneity-Based	Communication Model	Path Establishment
2012	[12]	✓	✓	✓													
2012	[13]		✓	✓	✓	✓											
2012	[14]	✓	✓	✓													
2013	[15]						✓	✓									
2013	[16]						✓	✓									
2014	[17]							✓	✓	✓	✓	✓					
2014	[18]						✓	✓									
2014	[19]		✓	✓	✓								✓				
2014	[20]		✓	✓	✓												
2015	[21]		✓	✓	✓	✓							✓	✓	✓		
2015	[22]		✓	✓	✓												
2017	[23]						✓			✓	✓					✓	
2018	[24]						✓	✓									✓
2020	[25]	✓	✓	✓		✓							✓	✓		✓	

3. The Proposed Taxonomy

Taking into account their mechanisms and parameters, we proposed in a previous work a new overall taxonomy dividing routing protocols in WSNs into nine categories, as shown in Figure 1 [26].

In the following, we detail each routing paradigm focusing on the latest protocols.

3.1. Application Type

Based on the use application, routing protocols can represent two main categories: event-driven and time-driven protocols, depending on whether the data packets will be sent following an event or periodically.

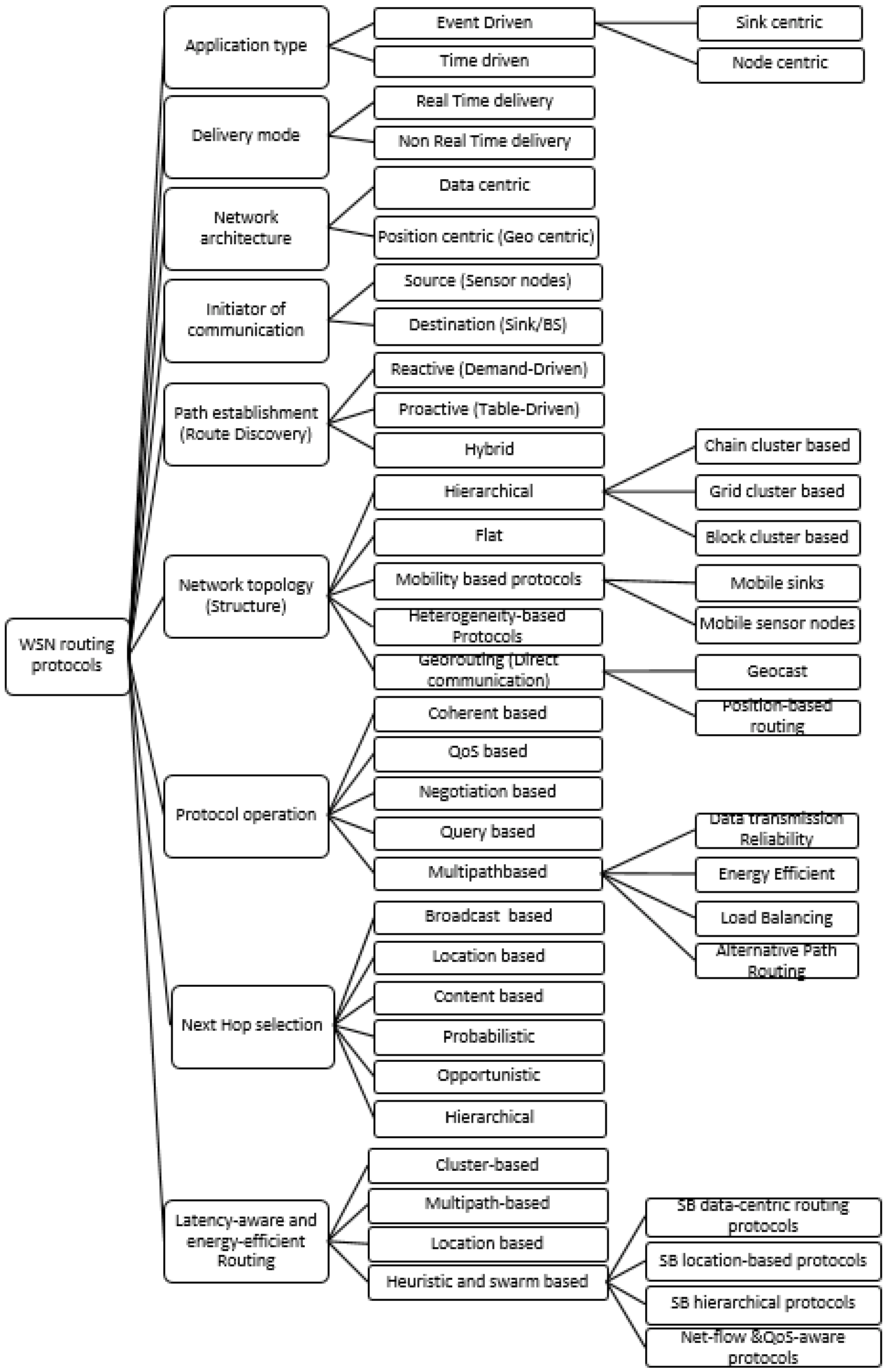

Figure 1. A taxonomy of routing protocols in WSNs.

3.1.1. Event-Driven

In event-driven protocols, a sensor node may send data only after the detection of a significant event over its sensing region, as shown in Figure 2. Those protocols are used in several domains thanks to their several advantages. In fact, they allow immediate detection of different triggered events. In addition, they permit to decrease the amount of communication and to avoid the unnecessary use of energy and computation resources of nodes. However, also, event-driven protocols present some limitations. Indeed, due to the fact that events are triggered randomly, the workloads will be unbalanced, and certain nodes will be activated more than the others. This will lead to the discharge and the death of some nodes, which can cause several problems, such as isolated areas.

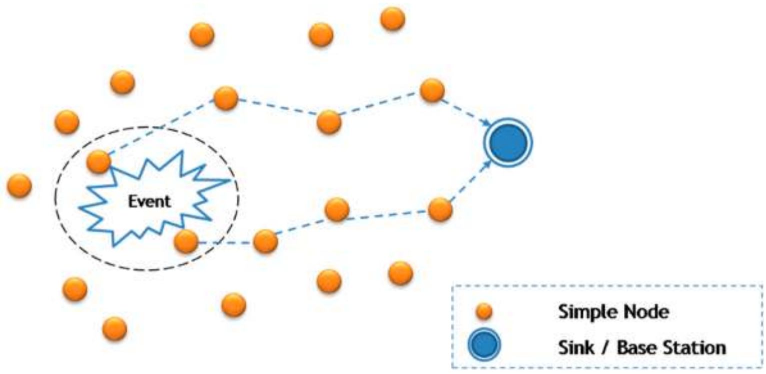

Figure 2. Event-driven routing model.

Many of WSNs' protocols are event-driven and can be classified into sink-centric or node-centric protocols.

Sink Centric

In these protocols, the sink manages the sensing levels and the routing decisions according to the collected information and sent by sensor nodes in the sensing area. Among the representative protocols of this class, we find:

- **Real-Time and Reliable Transport (RT)2 Protocol**

(RT) 2 is designed as a reliable and timely transport protocol using collaborative transportation of events [27]. It considers nodes as sensor nodes and actor nodes: When sensor nodes detect a triggered event, sensed data would be sent to the base station (BS) through active nodes. In (RT) 2, congestion is detected and controlled by actor nodes. In [28], the authors show that the (RT)2 protocol can adapt easily to the heterogeneous nature of WSNs by dint of its configuration and provides real-time communication and various reliability requirements, which helps in reducing energy consumption, but it consumes large amounts of the bandwidth.

- **Loss Tolerant Reliable Event Sensing (LTRES) Protocol**

Mainly designed for the dynamic event detection in WSNs, LTRES determines the event-sensing fidelity level (ESFE) according to which the end-nodes adjust their source rates [29]. It performs network traffic control, which is based on distributed source rate adaptation and ensures reliable event detection, but the use of the source rate adaptation mechanism makes it very greedy in energy.

- **Reliable Robust and Real-Time (RRRT) Protocol**

As a reliable and timely event detection transport protocol, RRRT uses a combined congestion control mechanism to achieve reliability and conserve energy [30]. Researchers in [18] have shown that RRRT protocol improves energy conserving and ensures reliable event detection due to the reporting frequency adjustments, but it presents high levels of extra overhead because of the congestion detection and control techniques.

- **Simultaneous Multiple Event-to-Sink Reliable Transport (SMESRT) Protocol**

It ensures multiple event detection in WSNS with the improved rate of energy consumption by dint of the combined payload control component as this protocol combines all payloads at an elected CH and sent only one packet to the sink, which provides less traffic. Despite having high levels of extra overhead, SMESRT has the advantage of assigning different reporting frequency for different events [31].

- **Congestion and Delay Aware Routing (CODAR) Protocol**

CODAR is designed to reduce the latency and to provide reliable routing of the critical data through different techniques of mitigation, congestion avoidance and End-to-end delivery data management. It divides the sensors into the critical nodes (nodes closer to the event) and regular nodes (nodes away from an event). Experiences in [30] show that this protocol avoids congested nodes to reduce congestion in the network has the advantage of delivering a high amount of the critical data within specified delays, but it remains unsuitable for large networks [32].

Node Centric

In these protocols, sensing levels are predefined at the sensors; thus, decisions following an event are made by the end-nodes and gathered data would be sent to the sinks. Among these protocols, we find:

- **Collaborative Event Detection and Tracking (CollECT) protocol**

Based on three main procedures, this protocol ensures fast and reliable events detection [33] in different types of WSNs. Among the strengths of this protocol is that it represents a fully distributed scheme protocol, which results in its high-speed events detection.

- **Energy Efficient-Low Latency Express Routing Protocol(EELLER)**

Based on the clustering mechanism, the EELLER protocol removes data redundancy and provides optimized routes to send data from end-nodes to sinks [34]. To send sensed data, EELLER builds the expressways based on a link factor, and then it sends aggregated data through formed clusters. In [35], researchers show that this protocol provides efficient energy management and precise even detection by dint of the data aggregation techniques, but it is less reliable.

- **Information Quality Aware Routing (IQAR) Protocol**

As an energy-efficiency protocol, IQAR uses IQ constraints to find the least-cost routing tree [36]. It allows nodes to make independently a decision about an event to check and track it. Research proves that this protocol optimizes the QoS and helps in saving delay and energy in the network but presents high levels of overheads [37].

- **Event Reliability Protocol (ERP)**

ERP is designed as a reliable and real-time event transmission protocol [38]. It uses a region-based selective retransmissions mechanism to minimize similar redundant data to avoid congestion. It offers reliable event transmission and avoids collision, but it has the disadvantage of being greedy in energy consumption.

- **Efficient Event Detection Protocol (EEDP)**

EEDP is designed as a reliable data transmission protocol for event monitoring applications that require fast detection and transmission of data [39]. It allows nodes to take accurate decisions based on the two rules, namely the simple decision rule (SDR) and composite decision rule (CDR). Researchers show that EEDP offers accurate event detection, but it is less reliable [32].

3.1.2. Time-Driven

Time detection is a central component in numerous WSNs applications, especially those with a content aspect. In time-driven protocols, sensed data are sent periodically, and the reporting period may be preconfigured or set during operation, depending on the requirements of the application. Technically, time-driven communication is easy to implement. In addition to that, sending nodes to sleep between transmissions help to conserve energy and consequently extending the network lifespan, but time-driven techniques need various synchronization and coordination mechanisms. Among the representative protocols of this class, we find:

- **Well-Balanced-Threshold sensitive Energy Efficient sensor Network *protocol* (WB-TEEN)**

This protocol is designed as a time-driven protocol with a distributed clustering model [40]. In fact, it is an improved version of the TEEN protocol [41]. Authors in [42] found that this protocol enhances energy conservation, but load balancing between nodes is not well handled.

Table 2 establishes a comparison between "application type"-based routing protocols [43].

Table 2. Comparison of application type-based routing protocols for WSNs.

Protocol.	Application Type			Reliability	Congestion Control	Energy Efficiency
	Time-Driven	Event-Driven				
		Sink-Centric	Node-Centric			
(RT) 2		✓		N A	N A	✓
LTRES		✓		N A	✓	N A
RRRT		✓		✓	N A	N A
SMESRT		✓		✓	N A	N A
CollECT			✓	✓	N A	N A
EELLER			✓	N A	N A	✓
IQAR			✓	N A	N A	✓
ERP			✓	✓	N A	N A
EEDP			✓	Low	✓	Low
WB-TEEN	✓			✓	N A	N A

3.2. *Delivery Mode*

In some applications, the sensed data can be sent far from any temporal constraint, and data always remains useful, unlike other applications that need even more exactness and require real-time communication. From here, we classified routing protocols into real-time protocols and non-real-time protocols. We detail these two types of message delivery requirements in the following.

3.2.1. Real-Time Delivery

A vast majority of WSNs applications are real-time, such as radiation monitoring, fire monitoring and medical surveillance, etc. and require a high level of temporal accuracy, otherwise sensed data become useless, or their value is decreasing after the time-bound. These applications are referenced as real-time applications. In WSNs, communication delays are dominant over processing delays. Therefore, communication latency must be bounded to enable real-time information delivery in such networks [41–46].

In the following, we quote some real-time routing protocols designed for the WSNs.

- **Real-Time Power-Aware Two Hop routing (PATH)**

PATH is designed as a real-time routing protocol using the two-hop neighbor information for routing decisions [47]. It uses dynamic power control to manage energy consumption and packet delay to reduce packet dropping and improve real-time routing. Its main components are the forwarding metric and policy, the delay estimator and the initiative drop control. In [48], the authors show that PATH reduces packet dropping and communications reliability.

- **Contention-based Beaconless Real-time Routing protocol (CBRR)**

CBRR exists in the two versions, namely CBRR one-hop and CBRR two-hop protocol. It uses a contention mechanism to collect the information of neighborhoods to ward off the limitations of beacon-based schemes and to enhance energy conservation. It uses a reactive mechanism to select the suitable next-hop forwarder, which offers the shortest wait delay. Experience shows that this protocol presents good results in terms of end-to-end delay, delivery ratio and energy management [49].

3.2.2. Non-Real-Time Delivery

Contrary to real-time applications, there are several sensor applications, such as some environment monitoring systems like water and soil surveillance and habitat monitoring [50], which do not define time conditions on the data delivery and are referenced as non-real-time applications. The routing protocol task is to ensure data delivery with a minimum of energy. All routing protocols that are not RT-protocols can be classified as NRT-protocols. There are some routing protocols that can work either in RT or NRT mode, such as:

- **On-demand Multi-hop Look ahead Real-time routing protocol (OMLRP)**

As a reliable routing protocol for WSNs, OMLRP uses a look-ahead message and a mechanism involving three phases, namely: multi-hop look-ahead trigger, look-ahead message exchange and multi-hop management. OMLRP can work either in real-time or in non-real-time mode. Simulations show that the OMLRP gives good management in terms of energy but overloads the network with control messages [51].

Table 3 establishes a comparison between delivery mode-based routing protocols [52].

Table 3. Delivery mode-based routing protocols for WSNs.

Protocol	Delivery Mode		RT-Type (Soft/Hard)	Energy Efficiency	Reliability
	RT Delivery	NRT Delivery			
PATH	✓		SRT	High	Medium
CBRR	✓		SRT	Medium	High
OMLRP	✓	✓	SRT	Low	High

3.3. Network Architecture

Another way to categorize routing protocols in WSNs is to classify them as data-centric or position-centric (geo-centric) routing protocol based on the network architecture. In the following, we detail those two classes.

3.3.1. Data-Centric

The use of random distributions by several sensor applications makes it impossible to use a global identification system to locate nodes, and consequently, the traditional address-based routing becomes non-applicable. Data-centric routing is a query-based strategy that overcomes these limitations and can adapt to this environment by dint of its naming mechanism base and the description of data in the queries [53]. The representative routing protocols in this category are:

- **ACtiveQUery forwarding In sensoR nEtworks (ACQUIRE)**

As a data-centric routing protocol, ACQUIRE uses an active querying mechanism that visualizes WSNs as a distributed database. It forwards the query at each node to be resolved partially in each hop. Hence, the active query becomes smaller and smaller until being resolved completely. ACQUIRE has the ability to manage complex queries, but it remains ineffective in terms of energy consumption [54].

- **RoUting on finGerprint Gradient in sEnsor networks (RUGGED)**

RUGGED is designed as a data-centric routing protocol. It routes the query to the event through a random node based on natural information gradient repository, probabilistic functions and the fingerprint of the event, which is an information gradient resulting from the occurring of a physical event in the environment. RUGGED provides reliable and efficient routing, but it is energy-intensive [55].

3.3.2. Position Centric (Geocentric)

Location-aware use the location information accessed from the GPS signals or received radio signal strength as forwarding metrics during the forwarding of queries to that particular region and to relay data to the destination in order to reduce transmissions. This family of protocols includes:

- **Minimum hop routing protocol (Min-Hop)**

Min-Hop is designed as a location-based energy-aware routing protocol. It forwards packets with minimum energy consumption based on the two phases: initialization and routing phase. During the initialization phase, min-hop builds the routing tables to be able to construct the optimal path to the destination, which is the shortest path used in the routing phase to forward packets to the destination. Using the short path, this protocol enhances the energy consumption, but the nodes forming this path will be overused and quickly die, which creates various problems such as isolated areas [56].

- **Path Energy Weight (PEW)**

PEW is designed as a location-based protocol. It uses a global view mechanism to globally map energy levels in the network [57]. The selection of forwarding routes in this protocol is made according to the energy distribution along paths, and the one with a balanced energy level will be promoted to avoid energy holes to improve the network lifespan.

Table 4 establishes a comparison between network architecture-based protocols.

Table 4. Network architecture-based protocols.

Protocol	Network Architecture		Data Aggregation	Scalability	Power Usage
	Data-Centric	Position Centric			
ACQUIRE	✓		✓	Low	Low
RUGGED	✓		N A	Low	N A
Min-Hop		✓	N A	Medium	N A
PEW		✓	N A	Medium	N A

3.4. Initiator of Communication

When any end-point of the network, whether the sensing nodes or the sinks, need to communicate with the other end-point, it will initiate the routing paths. In this way, we can classify the routing protocols based on whether they are source or destination initiated depending on whether the initiator of the communication is, respectively, the sensors (source) or the sink (destination).

3.4.1. Source

This type of routing protocol sets up the routing paths following the request of sensor nodes, which can need a service from the sink or to send their data. Thus, communication starts from nodes to sink.

3.4.2. Destination

Contrary to the first category, those routing protocols establish the routing paths following the request of sinks (or base stations) when they want to send packets to the sensor nodes. Hence, the communication starts from the sinks.

3.5. Path Establishment (Route Discovery)

According to the way of identifying or discovering possible routes, the routing protocol can be proactive, reactive or hybrid. Proactive protocols generate a routing table at each node containing all the routes before they are really needed using routing information, which is periodically updated. Reactive protocols do not generate routing tables and compute routes only if needed or on an on-demand basis. Finally, hybrid schemes combine the advantages of proactivity and reactivity. In the following, we detail those three classes.

3.5.1. Proactive (Table-Driven)

In proactive or table-driven routing protocols, the route is known prior to the requirement by dint of the maintenance of forwarding and an advertising table in the memory of every sensor node. The forwarding table contains a list of destinations, combined with one or more next-hop neighbors that lead toward these destinations in addition to the costs associated with each next-hop option and the advertised one records links and their variations as long as their status change using different methods to update them. Consequently, packets can be sent out to their destination immediately, without the delay imposed by route discovery. However, proactive protocols may be overly aggressive because a certain amount of control traffic, independently of data traffic on the network, is needed and must always be present to keep routing tables up to date and consistent over the whole network, which may consume large amounts of bandwidth and energy although many established routes may never be needed. Among recent proactive protocols used in WSNs, we find:

- **SinkTrail**

SinkTrail is a proactive routing protocol [58]. It uses logical coordinates to infer distances and selects the best route establishes for data reporting routes. It reduces energy consumption and supports mobile sinks in large-scale networks.

3.5.2. Reactive (Demand-Driven)

In contrast with proactive routing protocols, reactive protocols compute and establish routing paths only when it is necessary (on demand). This strategy is adopted in order to decrease the burden on the network and reduce energy consumption resulting in maintaining unnecessary information. When a sensor needs to establish a path, it triggers a process of route discovery and waits for the response. This process may take time to establish a routing path between nodes, which causes the packet delivery delay. The time-driven protocol TEEN presented previously is a reactive routing protocol. Many other reactive routing protocols are used in WSNs among them, we quote:

- **Ad Hoc On-Demand Distance Vector (AODV)**

AODV is a reactive protocol used in WSNs [59]. It uses a route request (RREQ) message sent by the source node. When a routing path is required, the destination responds by transmitting a route reply (RREP) message. Authors in [60] show that the AODV protocol reduces control traffic significantly by originating path requests on-demand but establishing routing paths between nodes may take time.

3.5.3. Hybrid

The main idea of hybrid protocols is to take advantage of proactive and reactive strategies and to exploit their merits in order to incorporate the benefits of proactivity and reactivity. Hybrid protocols are used to speed up delivery and reduce processing overhead by selecting the most efficient routing mechanism to use during packet routing.

3.6. Network Topology (Structure)

Another way to group routing protocols is to classify them based on the network structure (topology). The protocols included in this category are further divided into five broad subcategories according to their functionalities, which are: flat, hierarchical, mobility or heterogeneity-based and geo-routing protocols. We detail each of these categories below.

3.6.1. Hierarchical (Cluster-Based)

Hierarchical schemas define a specifically structured topology. They divide the sensor nodes into many groups called clusters, with a specially selected node in each group called the cluster head (CH). Those CHs coordinate and communicate directly between them or with the BS, as shown in Figure 3. Hierarchical routing protocols use several strategies to select the CH, e.g., the highest energy node or the one having the maximum number of neighbors in a cluster can be selected as CH. Hierarchical routing is an energy-efficient method aiming to maximize the network lifespan and to ensure network scalability through the hierarchical structure. These protocols can be classified into block, grid and chain cluster-based protocols.

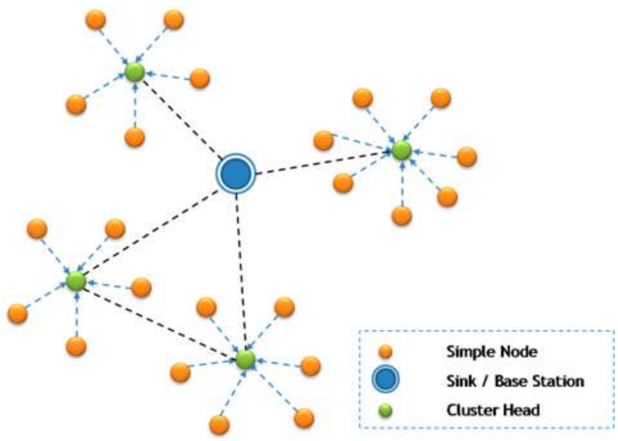

Figure 3. Hierarchical routing model.

Block Cluster-Based

These protocols divide and arrange nodes in a virtual block, then setup a networking strategy to manage communication in and between blocks. Among the representative protocols of this class, we find:

- **Chain Cluster-based Mixed (CCM)**

CCM takes advantage of LEACH [61] and PEGASIS [62] on which it is based. It uses a CH selection algorithm based on the remaining energy without considering its distance to the BS. This protocol organizes the sensor into a vertical cluster and horizontal chains and transmits packets in the two stages, namely chain routing and then cluster routing.

- **LEACH with Virtual Force (LEACH-VF)**

LEACH-VF combines the LEACH algorithm with the two types of virtual forces, which are the attractive force, used to move the nodes towards the cluster head, and the repulsive force used to move the overlapping nodes away from each other [63]. Simulations show that this strategy maximizes the coverage area and solves the difficulty of sensing holes, but energy efficiency remains very limited.

- **Hierarchical Clustering-based routing algorithm with Two cluster heads in each cluster for Energy balancing (HCTE)**

HCTE selects two CHs in each cluster and routes data packets from the CHs to the BS using a multi-hop mechanism to enhance the network lifespan. Each CH is responsible for different tasks in the cluster. Simulations show that HCTE avoids unbalanced energy consumption, but it does not achieve energy efficiency [64].

Grid Cluster-Based

These protocols divide the network into grids and arrange nodes accordingly. Then, they setup their own networking strategy to manage network communications. Among the representative protocols of this class, we quote:

- **Hierarchical Geographic Multicast Routing (HGMR)**

This protocol is a location-based multicast scheme [65]. It takes advantages of the geographic multicast routing (GMR) [66] to route packets along the multicast tree in one transmission, and it uses the hierarchical rendezvous point multicast (HRPM) [67] to decompose the multicast group into subgroups, which easily overcomes the problem of network scalability, but research shows that the used network distribution can affect the selection of the best routing paths which minimizes the effectiveness of routing task of HGMR.

- **SLGC**

SLGC is designed as a grid clustering algorithm. The CH of each cluster uses a single-method SLGC algorithm to send data queries to the BS. Research shows that this routing strategy makes it highly energy-efficient, but it overloads the network and incurs extra overhead in various cases such as complex data transmission [68].

Chain Cluster-Based

These protocols build chains of nodes with a well-defined strategy to manage communication between sensor nodes. Among the representative protocols of chain cluster-based class, we quote:

- **Concentric Clustering Scheme (CCS)**

CCS represents an extension of PEGASIS [69]. In fact, it reduces energy consumption and takes into account the BS location in order to improve the network lifespan and improve its performance. The CCS divides the sensing area into concentric circular tracks assigned with various levels and constructs chains inside the track similar to PEGASIS. Each CH transmits its location information to the upper and lower level CH, and each node aggregates and fuses its own data with data received from other sensors and transmits the generated data to the next node in the chain, which narrows the length of packets. Research shows that CCS conserves energy; however, long chains are responsible for large delays [70].

Table 5 establishes a comparison between hierarchical-based routing protocols [71].

Table 5. Routing protocols for WSNs.

Protocol	Network Topology: Hierarchical			Cluster Scalability	Scalability	Delivery Delay	Energy Efficiency
	Block Cluster-Based	Grid Cluster-Based	Chain Cluster-Based				
LEACH	✓			Medium	Very low	Very small	Very low
CCM	✓			High	Very low	Small	Very low
LEACH-VF	✓			High	Very low	Very small	Medium
HCTE	✓			Medium	Very low	Very small	Very low
SLGC		✓		Medium	Very low	Very small	Medium
HGMR		✓		High	Very high	Moderate	Medium
CCS			✓	Low	Low	Large	Low
PEGASIS			✓	Low	Very low	Very large	Low

3.6.2. Flat

This category of routing protocols defines a special network topology in which sensors are treated equally and have identical functionalities. The flat networking model is used with a very big number of sensors, which forbids the use of a global identification system. As in the case of Data-centric routing, flat routing protocols use a mechanism based on the naming and the description of data in the queries. Thereafter, data-centric routing protocols previously presented in this survey, such as ACQUIRE, are flat-based routing protocols.

3.6.3. Heterogeneity-Based

HHeterogeneity-based routing protocols are destined to a specific network topology in which there are several types of sensors, e.g., some sensor nodes can be battery-powered, and therefore it has a limited lifetime (battery-powered sensors), but others can have no energy constraint (line-powered sensors). Heterogeneity-based protocols manage to route and take advantage of unlimited or highest energy of some nodes to extend the network lifetime. When some sensors in the network are at one energy level while others nodes are at another, we talk about two levels of heterogeneity in the same way; WSNs can have three or more levels of heterogeneity if the network contains three or more categories of sensors with different energy levels. Some of the representative protocols in this category are:

- **Developed Distributed Energy-Efficient Clustering (DDEEC)**

This protocol is designed as a heterogeneity-based routing protocol and works at two levels of energy [72]. It presents an enhancement of the DEEC [73] protocol and uses some election probability functions to alternate the election of CHs between advance and normal nodes in order to remove the drawbacks of the DEEC election method. Research such as [74] shows that DDEEC outperforms DEEC in terms of network and stability period, but it presents some delays.

- **Threshold-Sensitive Stable Election Routing Protocol (TSEP) Protocol**

TSEP is designed as a three-level heterogeneity-based routing protocol [75]. In fact, it divides nodes into three categories based on their energies, which are: normal, intermediate and advance nodes and acts as a reactive routing protocol. Simulations in [76] prove that TSEP increases stability, network lifetime and network throughput but causes some delays.

- **Enhanced Developed Distributed Energy Efficient Clustering (EDDEEC)**

EDDEEC is designed as a three-level heterogeneity-based routing protocol [77]. It works in hierarchical networks and defines three types of sensors classified according to their energy levels into normal, advance and super nodes. Authors in [78] show that the scalability and the network lifetime is more efficient by using this protocol as compare to DEEC, but it presents some delays.

- **Balanced Energy Efficient Network Integrated Super Heterogeneous (BEENISH) Protocol**

This protocol is designed as a four-level heterogeneity-based routing protocol [79]. It defines four types of nodes, namely normal, advance, super and ultra-super nodes, based on their energy levels. This protocol also works in a hierarchical context and uses some election probability functions in CH election. Simulations show that this protocol enhances the stability period, the throughput and the network lifetime as compare to DDEEC, TSEP and EDDEEC.

Table 6 establishes a comparison between heterogeneity-based routing protocols [80].

Table 6. Comparison of heterogeneity-based routing protocols for WSNs.

Protocol	Heterogeneity Level	Network Lifetime
DDEEC	2	Medium
TSEP	3	Medium
EDDEEC	3	High
BEENISH	4	High

3.6.4. Mobility-Based Protocols

After their deployment, sensor nodes are able to change their position in some cases due to the influences of several factors such as mobile platform, environmental conditions (wind, water ...), and physical security or by the personal intervention [81] in addition to the sinks that can be mobile for needs of coverage or connection. Hence, we can a mobile sensor nodes or mobile sinks. Mobility results in frequent changes in network structure, which in turn introduces several problems such as route changes, packet delivery delay, isolated areas, etc. The mobility-based protocols, either for mobile sensor nodes or mobile sinks, are designed to adapt to this mobility, overcome these problems and enhance the network lifespan.

Mobile Sinks-Based Routing Protocols

Those routing protocols are used in some WSNs where sink nodes are mobile. Among these protocols, we find:

- **Meeting Position Aware Routing (MPAR) protocol**

MPAR is designed as a query-based routing protocol for WSNs using mobile sinks [82]. In fact, sinks send out a query message containing geographic information and some other parameters used by source nodes to calculate the estimate propagation time (EPT) used by the relay nodes to calculate the estimated meeting position (EMP) to predict the position of the mobile sink to send queried data to the predicted position. Simulations results show that MPAR is very effective in energy and delivery latency.

Mobile Sensor Nodes-Based Routing Protocols

This category of protocols is designed for WSNs in which sensor nodes support mobility. Among these protocols, we find:

- **Mobility-based clustering protocol (MBC)**

MBC is designed as a proactive hierarchical routing protocol supporting mobile sensor nodes in WSNs [83]. It is inspired by the LEACH-M protocol and cluster-based routing protocol (CBR) [84]. Indeed, it selects the CHs according to the mobility and the residual energy. This protocol ensures reliable paths to allow mobile nodes to join the appropriate CH without packet loss. In [85], the authors show that MBC increases PDR and reduces energy consumptions in WSNs.

- **Energy-Efficient and Fault-Tolerant Routing Protocol for Mobile Sensor Network (FTCP-MWSN)**

FTCP-MWSN is designed as hierarchical routing protocols for mobile nodes in WSNs [86]. To conserve energy, sensors send small-sized packets to the CH, which sends the ID of nodes to the BS in order to achieve reliability and provide fault tolerance. Simulations have proven the energy efficiency of FTCP-MWSN that can detect the failure of sensor nodes, but it presents some end-to-end delay.

Table 7 establishes a comparison between mobile-sensor-node-based routing protocols [87].

Table 7. Comparison of mobile-node-based routing protocols for WSNs.

Protocol	Mobility-Based		Fault Tolerance	Energy Efficiency	Load Balancing
	Mobile Sink	Mobile Sensor Nodes			
MBC		✓	N A	✓	N A
FTCP-MWSN		✓	✓	✓	N A

3.6.5. Geo-Routing (Direct Communication)

Geographic routing is based on the positions of the nodes. These protocols can generally be divided into the two broad subcategories, namely: geocasting and position-based routing, depending on whether the data are retrieved from several nodes located in a particular region or from a single source node. In the following, we detail these two classes.

Position-Based Routing

In position-based routing, sensors are aware of their geographic location, and they are addressed based on their GPS location and via node coordination. In fact, the position of the source, the intermediate nodes and the destination should be known to help the routing process, which limits the role of routing tables and can help in energy consumption.

In general, this type of routing strategy contains two phases: a location service provides a source node with the position of the desired destination then it defines the routing path from source to destination [88].

Geocast

In some cases, the detection of an event or of a particular phenomenon requires the collaboration of several sensor nodes. Indeed, only one sensor node can provide limited or inaccurate information. Instead of a single node, geo-casting addresses all sensors in a particular static geographic region determined by the source node or constructed dynamically by the relaying of some sensors. Geocast routing uses different routing strategies to forward packets to the desired geographic destination, such as unicast transmission and flooding [89]. Among the geocast routing protocols used in WSNs, we find:

- **GeoGRID**

GeoGRID is designed as a geocasting protocol for WSNs [90]. It divides the destination region into grids. It uses a preselected routing path through the nodes to forward packets to the desired area. This increases the reliability and robustness of the protocol, but they cause a network overload. Research, such as [91], show that GeoGRID requires some optimizations that enables the workload distribution to be dynamically adjacent to extend the network lifespan.

3.7. Protocol Operation

Another way to classify routing protocols in WSNs is to classify them according to the protocol operation. This category can be divided into five broad subcategories depending on protocol procedures. These subcategories are multipath, query, negotiation, QoS and coherent-based routing protocols. Each of these classes is detailed in the following.

3.7.1. Multipath-Based

This class is widely used in WSNs to enhance the performance of the network. Indeed, multipath-based protocols use multiple paths to route data between the source and the destination in order to balance the traffic load in the network, to provide reliability and robustness in the case of node failures [92] and to alleviate congestion [93]. Multipath-based routing protocols class may be further divided into four subclasses, which are: alternative path routing, load balancing, energy-efficient and data transmission reliability. These subclasses are detailed in the following.

Alternative-Path Routing

Alternate-path-based routing protocols provide high-level route failure protection through the construction and the maintenance of multiple paths between communicating nodes. These routing paths are not used simultaneously; only one path is used for packet transmission and will be changed by another in the case of breakdown. The other paths are kept ready in the case of need [94]. Among the alternative-path-based routing protocols, we find:

- **Braided Multipath Routing (BMR) Protocol**

BMR is designed as an alternative path-based routing protocol [95]. It builds multiple alternative paths called braided multipath, which is partially disjoint from the original path so that it contains a minimum number of nodes that belong to the main path to the increase resilience to node failure. BMR uses control packets to manage those paths, which causes a network overload. Research, such as [96], shows that an alternate node-disjoint path leads to the consumption of more energy seen that it is longer than the original path.

- **An Efficient Fault-Tolerant Multipath Routing Protocol (HDMRP)**

HDMRP is designed for heterogeneous WSNs in which we found the root nodes and the sub-roots, which are successively the sink neighbors and root neighbors [97]. It constructs multiple disjoint paths to the sink using route request (RREQ) messages.

Load Balancing

This mechanism minimizes traffic congestion. In fact, when the main link is over-utilized, the load balancing mechanism uses alternative paths to divert traffic in order to alleviate congestion. Among these protocols, we find:

- **Meshed Multipath Routing (M-MPR)**

The Multipath routing protocol M-MPR distributes traffic along a meshed path to avoid traffic congestion, and it uses a selective forwarding (SF) technique to ensure efficiency and to maximize the packet delivery rate. This protocol presents several advantages, especially in terms of energy conservation, e.g., routing table and packet lengths are reduced because of many sources to one destination route discovery strategy. In addition to that, M-MPR allows a node to forward only one of possibly many received packets from its peripheral sources to the destination. However, on the other side, research shows that M-MPR presents some delays [98].

Energy-Efficient

These protocols aim to select the route that requires less energy among available paths in order to enhance the network lifespan. Among multipath energy-efficient routing protocols, we find:

- **Energy-Efficient and Collision-Aware Multipath Routing Protocol (EECA)**

EECA [99] utilizes the node position information to adjust transmission power and uses collision avoidance techniques based on the broadcast nature of wireless communications without extra overhead to improve energy efficiency and communication reliability. Research shows that the resource utilization and the end-to-end delay can be reduced through data transmission over minimum-hop paths, but using such paths increases the risk of packet loss, also the need to be GPS-assisted increases the cost of network deployment [100].

- **Low-Interference Energy-Efficient Multipath Routing Protocol (LIEMRO)**

LIEMRO is an energy-efficient multipath protocol. It uses multiple interference-minimized node disjoint paths between communicating nodes to minimize interference over and route coupling effect to improve the network lifespan, PDR and latency, but the effects of service rate of the active nodes and its buffer capacity are not considered in the estimation and adjustment of the traffic rate of the active paths [101].

Data Transmission Reliability

In order to the increase network reliability and to improve the probability of successful packet delivery, some multipath-based routing protocols send multiple copies of data simultaneously through many available paths. Among these protocols, we find:

- **Multi-Constrained QoS Multipath Routing (MCMP)**

MCMP is a multipath routing protocol. It uses multiple braided paths to route data to the sink node taking into consideration the shortest route to augment the network performance according to certain QoS requirements with moderate energy cost. The significant interference caused by high data rate transmission of redundant data isthe major disadvantage of this protocol [102].

- **Energy Constrained Multipath Routing (ECMP)**

ECMP presents an enhancement of MCMP. Indeed, it improves the QoS and the energy conservation in the network and formulates the routing problem as an energy optimization issue strained by the reliability and geospatial path selection. In fact, compared to MCMP, in which next-hop neighboring nodes are selected randomly without energy consideration, ECMP attenuates the selection of next-hop nodes based on the energy efficiency of paths, but the two protocols are equivalent in terms of delivery ratio and transmission delay [103].

Table 8 establishes a comparison between multipath-based routing protocols [104].

Table 8. Comparison of multipath-based routing protocols for WSNs.

Protocol	Network Operation: Multipath-Based				Path Disjointedness	Energy Efficiency	Reliability	Fault Tolerance	QoS
	Alternative Path Routing	Load Balancing	Energy-Efficient	Data Transmission Reliability					
BMR	✓				Node-disjoint	Yes	N A	Yes	N A
HDMRP	✓				Node-disjoint	No	No	Yes	No
M-MPR		✓			Node-disjoint	No	No	No	No
EECA			✓		Node-disjoint	Yes	N A	N A	N A
LIEMRO			✓		Node-disjoint	Yes	N A	N A	N A
MCMP				✓	Partially-disjoint	No	Yes	No	Yes
ECMP				✓	Partially-disjoint	Yes	Yes	No	Yes

3.7.2. Query-Based

Query-based routing protocols are mainly energy savers and can be adapted for networks in which geographic routing information is not available. In these protocols, the BS initiates the communication based on query packets used to retrieve data from the sensor. A path is generated while the query propagates through the network to be used as a data return path. The data-centric protocol ACQUIRE is counted in query-based routing protocols.

3.7.3. Negotiation-Based

These protocols are based on a negotiation process between neighboring nodes. This process is performed by naming the data using high-level data descriptors before sending it to ensure that there is no duplicate information sent throughout the network, which helps to reduce energy consumption. Researchers in [105] propose the sensor protocols for information via negotiation protocol (SPIN) on which several other protocols were based as described in Table 9:

Table 9. Family routing protocols.

Protocol	Description
SPIN-PP [106]	Intended to p2p communication networks.
SPIN-EC	Same as SPIN-PP, but with limited energy.
SPIN-BC	Optimized for broadcast channels.
SPIN-RL	Specifically used in cases of channel loss in broadcast networks.
M-SPIN [107]	Transmit data only to sink node instead of the whole network to save energy.

The SPIN-based routing protocols use resource-adaptive algorithms and data negotiation.

3.7.4. QoS-Based

QoS-based routing protocols take into consideration the QoS requirements in addition to minimizing energy consumption in the network. In fact, QoS metrics such as reliability, delay and bandwidth must be satisfied when routing data packets to the destination. Multipath-based protocols MCMP and ECMP, presented previously, belong to this class. Among other QoS-based routing protocols, we find:

- **QoS-based energy-efficient sensor routing (QuESt) protocol**

QuESt protocol is designed as a QoS-based protocol. It uses the multi objective genetic algorithm (MOGA) to determine optimal routes by optimizing multiple QoS parameters. Although this protocol is able to recognize a group of QoS-based close ideal paths, congestion treatment is not mentioned in this protocol [107].

3.7.5. Coherent-Based

Data processing is a major task in WSNs. Hence, different mechanisms are used to reduce the processing costs to conserve energy. In this context, collected information can be processed using a coherent or non-coherent method. In non-coherent protocols, nodes will locally process the sensed data, contrary to the coherent data processing-based protocols where a minimum processing is done locally by the sensor nodes. In [108], the authors have proposed single, and multiple winner algorithms (SWE and MWE) used, respectively, for non-coherent and coherent processing. In the SWE, a single aggregator sensor is selected for complex processing based on its computational capabilities and remaining energy. The MWE is an extension of the SWE algorithm. It limits the number of source nodes that can send data to the central aggregator node in order to limit energy consumption.

3.8. Next-Hop Selection

As with all routing protocols, each sensor selects the next-hop towards the destination according to a set of information. The next-hop can be selected in different ways such as Broadcast based, location-based, content-based, probabilistic, opportunistic and hierarchical-based protocols. We detail each of these categories in the following.

3.8.1. Broadcast-Based

In broadcast-based protocols, nodes must distribute packets to every node in the WSNs. In fact, each node broadcasts the packet to its neighbors, where it will be re-broadcasted. The minimum cost forwarding algorithm (MCFA) is based on a broadcasting mechanism where each node broadcasts each message to its neighbors. Limited network size and unbalanced loads are the major disadvantages of this mechanism [109].

3.8.2. Location-Based

As explained previously in this survey, these routing protocols use geographic information in the selection of the next-hop in order to relay data to the destination, which eliminates the number of transmissions significantly.

3.8.3. Content-Based

In some communication models, messages are not given explicit destination addresses, so that next-hops and routing information must be inferred from the sensed data carried by the message.

3.8.4. Probabilistic

Probabilistic-based protocols assume that all nodes are homogeneous and randomly disseminated and select in a random way the next-hop among available sensors to enhance load-balancing and increased robustness. Authors in [110] present EAR, which associates a probability of use to each routing path according to the remaining energy of sensors that form it. Simulation results show the presence of some delays.

3.8.5. Opportunistic

Opportunistic routing (OR) algorithms differ by the chosen metric applied to the forwarder selection and prioritization. Hence, several opportunistic routing protocols have been presented depending on several metrics such as the real-time opportunistic routing protocol (ORTR) [111], which adjust the transmission power to follow the delay constrains and the energy-aware opportunistic routing protocol (EAOR) [112], including crucial energy information exchange during the well-know RTS/CTS handshake of opportunistic routing protocol [113]. The objective is to define a new OR metric, which reduces energy consumption in WSNs.

3.8.6. Hierarchical

The hierarchical-based routing protocol uses a hierarchical-based scheme that organizes the next-hop selection and should be respected along the routing paths, as explained previously in this survey.

3.9. Latency Aware and Energy-Efficient Routing

These protocols extend the network lifetime despite the poor processing and storage capacity of nodes. These protocols can generally be divided into four broad subcategories, which are: cluster, multipath, location, heuristic and swarm-based protocols. In the following, we detail these classes.

3.9.1. Cluster-Based

The hierarchical scheme of cluster-based protocols aims to balance the energy efficiency and delay metrics in order to enhance the network lifespan. As explained earlier in this survey, several routing protocols have been proposed and have attempted, in different ways, to achieve energy efficiency in WSNs.

3.9.2. Multipath

As explained previously in this survey, this category of protocols is based on multiple routing paths instead of a single path to transmit data between communicating nodes to balance the traffic load in the network. Multipath routing protocols are able to find the path with the lowest cost while meeting the network latency in the network.

3.9.3. Location-Based

These protocols can be used when nodes know to become aware of their location. They are used to ensure network latency and to avoid congestion to achieve energy efficiency, as explained earlier in this survey.

3.9.4. Heuristic and Swarm-Based

These protocols were inspired by natural behaviors as ant and bee colonies. Several protocols were developed based on this concept, such as the framework of ant colony optimization (ACO) [114,115], mainly aiming to enhance the network lifespan. Protocols belonging to this class are further divided into four subcategories according to their functionalities, which are: SB data-centric, SB location, SB hierarchical and network flow and QoS-aware protocols. Each of these categories is detailed in the following.

SB Data-Centric Routing Protocols

Some swarm-based protocols are data-centric-based and aim to improve network reliability and lifespan using various techniques. Among those protocols, we find:

- **Pheromone-based energy-aware Directed Diffusion (PEADD)**

This protocol involves sensors with higher energy levels in the data gathering process in order to enhance the network lifetime [116]. Inspired from ant colonies, where a chemical substance known as a pheromone is used to sign food paths, PEADD increases routes with larger energy while others are reduced depending on the remaining energy to which the pheromone is linked. PEADD updates the pheromone level based on the amount of transmitted data.

SB Location-Based Protocols

Some swarm-based protocols use location information to estimate the distance between two sensors and to enhance the performance of the routing process in order to conserve energy in WSNs. Among the representative protocols of this class, we quote:

- **Sensor-driven and cost-aware ant routing (SC)**

Inspired by ant colonies, SC assumes that ants (sensors) know the location of the food (data) and aims to choose the best path to take initially. SC allows nodes to estimate routing costs through each of the sensor nodes, but when an obstacle arises in the routing path, SC suffers from redundant data and sensing errors [117].

SB Hierarchical Protocols

Swarm-based hierarchical routing protocols define a specific structured similar to ant colonies where eggs and larvae are grouped according to their degree of similarity into small groups. Among these protocols, we find:

- **Self-organizing data gathering scheme (SDG scheme)**

SDG is designed as a hierarchical protocol and allows nodes to use another sink in needed to ensure scalability and reliability. In SDG, the node clustering mechanism is similar to the way in which larvae and eggs are grouped in ant colonies. Researchers found that SDG reaches more than 90% of reliability even in the presence of loss channels, but a significant amount of energy is lost through the exchange of control packets due to the proactive nature of this protocol [118].

Network Flow and QoS-Aware Protocols

Satisfying the QoS of a network is the main objective of the routing protocols in WSNs. This category of protocols aims to deal with the loss of data packets and to guarantee their sequencing using some mechanisms inspired by behaviors observed in nature. Among these protocols, we find:

- **Energy-efficient ACO-based QoS routing (EAQR)**

EAQR is designed as a QoS aware routing protocol. It uses an improved ant colony optimization algorithm and a new dual pheromone heuristic model to ensure the QoS and balance the energy consumption over the network, but it presents some delays [119].

Table 10 establishes a comparison between heuristic and swarm-based routing protocols [120].

Table 10. Comparison between heuristic and swarm-based routing protocols for WSNs.

Protocol	Heuristic and Swarm-Based				Energy Efficiency	Data Aggregation	Route Selection
	SB Data-Centric Routing Protocols	SB Location-Based Protocols	SB Hierarchical Protocols	Network Flow and QoS-Aware Protocols			
PEADD	✓				Strong	Yes	Reactive
SC		✓			Strong	No	Hybrid
SDG			✓		Strong	Yes	Proactive
EAQR				✓	Strong	No	Proactive

Table 11 establishes a comparison between some routing protocols from different categories [121].

Table 11. Between different types of routing protocols for WSNs.

Protocol	Reliability	Congestion Control	Energy Efficiency	Data Aggregation	Scalability	Delivery Delay	Network Lifetime	Fault Tolerance	QoS
EEDP	Low	✓	Low	N A	N A	Moderate	N A	N A	N A
RACE	Medium	N A	High	N A	Low	Low	N A	N A	N A
PEW	Medium	N A	N A	N A	Medium	N A	N A	N A	N A
HGMR	Medium	✓	Medium	N A	Very High	Moderate	High	N A	✓
BEENISH	N A	N A	High	N A	N A	Moderate	High	N A	N A
FTCP-MWSN	N A	N A	Medium	N A	Medium	N A	N A	✓	N A
EQSR	Medium	N A	Medium	N A	Low	Moderate	N A	✓	✓
M-SPIN	Low	N A	Medium	Yes	Low	N A	N A	N A	N A
EAQR	N A	N A	High	No	Medium	N A	Medium	N A	N A

4. Simulation Results

To evaluate the performance of the most known protocols in WSNs, a sensing area of 100 m × 100 m containing 100 sensors with a sink in the center is designed under the NS3 simulator. The next subsection describes the parameters of the model used to compare LEACH, Mod-LEACH, iLEACH, E-DEEC, multichain-PEGASIS and M-GEAR protocols.

4.1. Energy and Network Model

The energy consumed to transmit k bits between the transmitter and a receiver separated by a distance d using a free space channel is calculated by Equation (1) [122]:

$$E_{Tx}(k,d) = k * (E_{elec} + \varepsilon_{fs} * d^2), d <= Td \tag{1}$$

Equation (1) Transmission energy though a free space channel
Or through multipath channel model using Equation (2):

$$E_{Tx}\ (k,d) = k * (E_{elec} + \varepsilon_{ms} * d^4), d > Td \tag{2}$$

Equation (2) Transmission energy through a multipath channel model
While the reception of k bits requires the energy calculated by Equation (3):

$$E_{Rx}(k) = E_{elec} * k \tag{3}$$

Equation (3) Reception energy of k bits
Knowing that threshold distance is calculated by Equation (4):

$$Td = SQRT\ (\varepsilon_{fs} / \varepsilon_{ms}) \tag{4}$$

Equation (4) Threshold distance value

Note that εfs presents the amplifier energy consumption used to maintain an acceptable signal in a free space channel model while εmp is used in multipath fading channel model depending on a chosen acceptable bit-error-rate.

As indicated in Table 12, a packet of 4000 bits is used during this comparison, and the confidence interval is taken to get precise plots.

Table 12. Model parameters.

Network Parameters	Values
Sensing area	100 m × 100 m
Nbr of sensors	100
Location of the sink	50, 50
Packet size	4000 bits
Sensor energy	0.5 J
Energy consumption on the circuit (E_{elec})	50nJ/ bit
Dissipation energy (Efs)	10 pJ/ bit/ m^2
Transmission energy (ETx)	50 nJ
Reception energy (ERx)	50 nJ
Data aggregation	5 nJ/ bit/ report

4.2. Simulation Results and Performance Evaluation

In the following, the protocols are compared in terms of network lifetime, stability/instability periods and energy consumption.

- **Network lifetime**

The network lifetime can be defined as the duration between the start of the simulation and the death of the last node of the network. The main objective of routing protocols is to extend the network lifespan to the maximum while keeping the QoS. The evolution of the network lifespan of the compared protocols is shown in Figure 4.

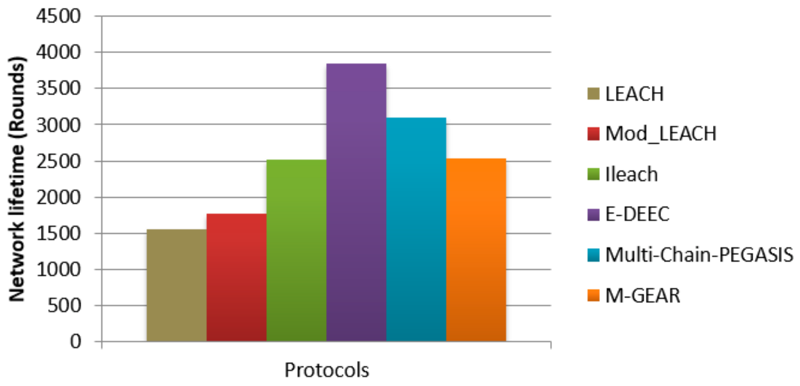

Figure 4. Network lifetimes.

The random CHs selection mechanism adopted by LEACH and Mod-LEACH protocols is the reason for the limited network lifetime. In fact, several nodes can simultaneously take the role of a CH without any need. This affects the energy of the sensors and then creates several isolated areas. Contrariwise, ILEACH and M-GEAR ensure a longer network lifetime. This is explained, respectively by the positive effect of the energy management function and the use of data aggregation tree-based on a multi-hop model in the case of iLEACH and due to the direct communication mechanism in the non-clustered regions and the use of a rechargeable gateway in the case of M-GEAR. The network lifetime is more important with E-DEEC and multichain-PEGASISIn fact, the existence of several types of nodes in the case of E-DEEC improves the energy efficiency of the WSN and guarantees better coverage while the Sink mobility ensured by multichain-PEGASIS protocol causes good load balancing and offers a long lifetime.

- **Stability/instability periods**

The network lifespan is made up of the two adjoining parts. The first part, starting from the beginning of the network until the death of the first node, is called the period of the stability, contrary to the instability period, which starts from the death of the first node until the last one in the network. Figure 5 shows these two periods for the compared protocols. Multichain-PEGASIS presents the best stability period with more than 1650 rounds. This is explained by the energy gain caused by the sink mobility, while the best period of instability is achieved by E-DEEC protocol thanks to the high energy levels of some sensors.

- **Remaining energy**

The remaining energy, shown in Figure 6, presents the total energy remaining in the battery of the sensors at round R.

Data routing is the most energy-consuming task in WSNs. Hence, the routing protocol must take maximum advantage of intelligent techniques to reduce energy consumption. Figure 6 shows that E-DEEC and multichain-PEGASIS manage the energy of the network in an optimized way due to the techniques used by these protocols like mobility, direct communication, and the use of various energy levels, which significantly improve the energy conservation in WSNs.

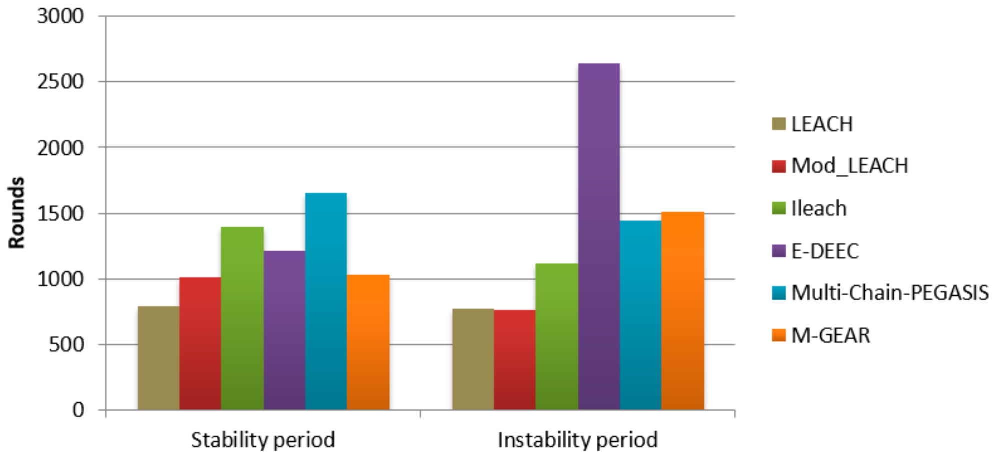

Figure 5. Stability and instability periods.

The energy variance (EV), shown in Figure 7, reflects the difference of residual energy of each node in the network, which can be affected by several parameters such as distribution, sensor location and activity rate.

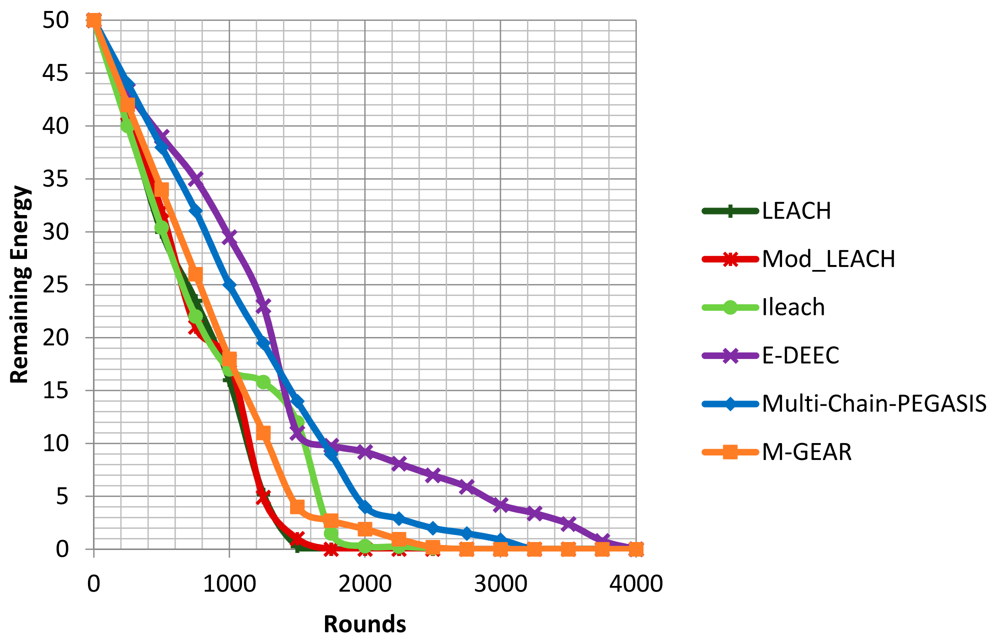

Figure 6. Energy versus rounds.

The shape and the volatility of the EV curves give us more precise and readable information about the load balancing in the network. In fact, the smaller the value and the smaller the curve fluctuation, the more balanced the energy of the network. Hence, the multi-chain PEGASIS protocol presents the best results explained by the positive effect of sink mobility.

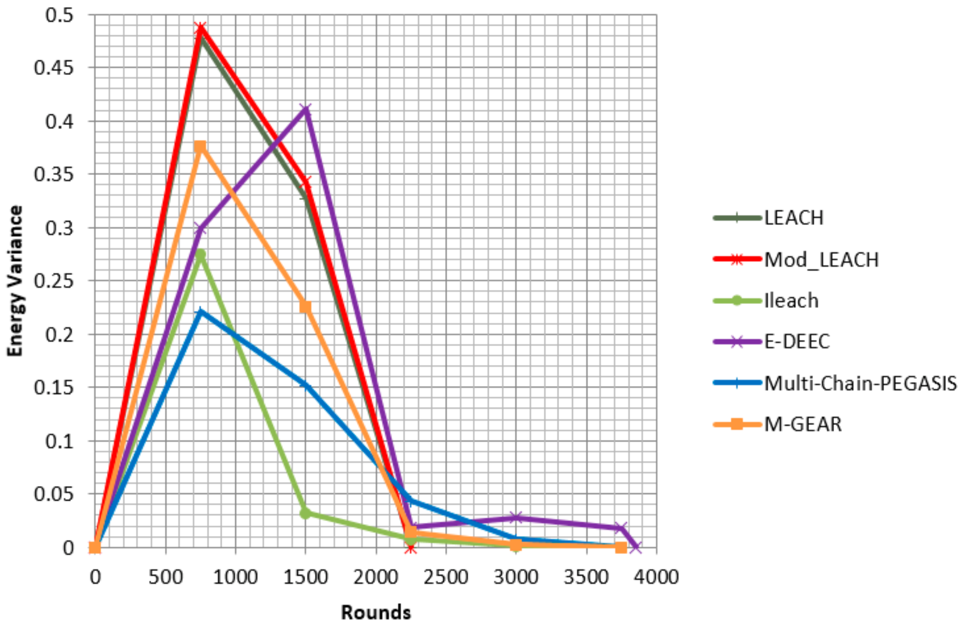

Figure 7. Variance versus rounds.

5. Conclusions and FUTURE Work

The emergence of WSNs in supporting a wide variety of applications has motivated researchers and attracted considerable attention in recent years, which makes routing tasks in WSNs among the most active and challenging research areas. We present in this paper a survey of routing mechanisms and protocols proposed for WSNs following a new deep classification model. In fact, we classified the mainstream recent proposed protocols using our taxonomy into nine categories of protocols, namely: application type, delivery mode, initiator of communication, network architecture, path establishment (route discovery), network topology (structure), protocol operation, next-hop selection, and latency-aware and energy-efficient routing. A detailed classification was presented under all the categories with the mention of its recent routing protocols. Furthermore, a performance evaluation of the most representative protocols is conducted under the NS3 simulator. Obtained results show that the E-DEEC, multichain-PEGASIS and M-GEAR protocols improve the network lifetime compared to other protocol which led us to conclude that on the use of smart techniques enhances the network lifespan and guarantee better coverage in the sensing area.

As future work, we will prepare an in-depth analysis of routing attacks and security mechanisms in WSNs with proved analysis by simulations to facilitate the conception of smart and secure routing protocols for researchers.

Author Contributions: R.Z. design, validation, data curation, review and supervise; A.K. theoretical study, analysis, findings, simulation scenarios and wrote the manuscript. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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