WSN Hierarchical Routing Protocol Taxonomy

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***Abstract*—Routing protocols in wireless sensor networks are generally focused on hierarchical infrastructures, for energy saving reasons. In this paper, we intend to give a taxonomy of these approaches identifying three criteria of classification: the assumptions, the algorithms and their evaluation. We classify projects based on these parameters and we also draw a uniform view over them, which may provide a basis of comparison for different routing protocols built atop hierarchical WSN infrastructures.**
Keywords: sensor networks, hierarchical routing, taxonomy, topology control, embedded systems

I. Introduction

Technology makes it possible to equip the environment with embedded computation and control devices which gather and process information from different sources improving the situation awareness. To achieve this vision, computation and control need to be coupled with communication: information should be transferred from source devices to actuator devices, or to end users. Therefore, networking technologies bring together embedded devices in order to enlarge and to give thorough vision of the physical environment.

Wireless sensor networks (WSNs) are made of individual nodes (called sensors) which are able to interact with the environment by sensing or controlling physical parameters. Some of the most popular sensing parameters integrated in a WSN node are: temperature, humidity, visual and infrared light, acoustic vibration, pressure and mechanical stress.

Most WSN applications distinguish the sources of data - the sensors - from the node(s) where the data should be delivered to, these nodes being called *sink(s)* or *base station*(s). The sink nodes generally dispose of more resources than the data source nodes.

The other components which make possible computation and communication for a wireless networked sensor device are: the low-power embedded processor, the memory, the radio transceiver and the power source.

Environmental monitoring based on the potential of embedded systems has been encouraged by the necessities of different application areas: agriculture, industrial automation, transportation, energy, medecine, military. These different applications outline a major expected feature for WSNs, scalability, commonly in number of sensor nodes. This makes direct communication between any sender and any receiver limited (only possible using prohibitively high transmission power). Several hops may be needed in communicating information, through intermediate relay nodes. These networks are defined as multi-hop communication infrastructures. One particular class of routing algorithms addresses the hierarchical-based topologies and is called hierarchical routing. Known to perform energy-efficient routing in WSNs, these techniques have special advantages related to scalability due to a particular topology control.

We intend to analyze and structure these kinds of approaches, identify common trends and finally make a classification of existing projects. The goal of the general taxonomy given here is to provide criteria to allow comparison of hierarchical routing in wireless sensor networks. The taxonomy we propose is meant to be complementary of those presented in [1] and [2], which address WSN routing regardless the topology.

The remainder of this paper is structured as follows: the next section identifies parameters needed for the taxonomy, corresponding to existing works in the field of hierarchical routing protocols for wireless sensor networks. Eleven approaches are exemplified in this taxonomy: LEACH [3], SOP [4], Hierarchical PEGASIS [5], HPAR [6], APTEEN [7], CMLDA [8], TTDD [9], Hierarchical Clustering [10], HEED [11], energy*delay approach [12], Top-Down approach [13] (given here in the order of their year of publication). The next section details each of the identified parameters and illustrates how different projects use them. Finally we draw a synthetic chart of projects, this time based on the parameters of the taxonomy.

II. Taxonomy parameters

The main objective of any routing protocol is to efficiently relay the sensed data. Three main features help structuring a hierarchical routing protocol design: the assumptions made about the system, the algorithms involved and their evaluation.

a) Assumptions: Efficiency depends directly on judicious use of topology control, which can significantly improve the network lifetime. The idea is to deliberately define, on the basis of some metrics, the set of nodes considered to be neighbors of a given node. In this way, the view of the network is no longer global, but focused on the neighboring area of particular nodes. Neighborhood is defined in different ways in literature and is influenced by some assumptions on the system. Looking into routing protocols based on hierarchical topologies, we identify three main parameters involved in the topology control and routing protocol: the level of heterogeneity/homogeneity of sensors, the communication energy model, the degree of mobility.

Heterogeneity may be involved at the hardware level (battery energy, hardware complexity, special hardware equipment, processing and communication capabilities) or at the software level (operating system support, software/programming support). The degree of heterogeneity in WSNs is an important assumption factor because it influences the complexity of the embedded software, the energy drainage (uniform or not) and the hardware cost. Generally, heterogeneous networks achieve a lower hardware cost, while homogeneous ones make energy drains uniform, when considering per node communication (nodes transmitting or receiving the same number of messages drains the same energy).

The second important assumption concerns the **energy** feature. The node communication components are the ones consuming most of the energy on a typical wireless sensor node. A thorough energy consumption characterization is critical for designing efficient routing protocols.

The third assumption concerns the of nodes **mobility**. For wireless sensor networks, integration of mobility (at any level, node, sink or event - the latter being less commonly met) implies support in the communication protocols. Mobility influences, just like heterogeneity, or the energy consumption model, the topology of the network: infrastructures become dynamic, so the knowledge on the current context (context awareness) needs to be updated.

b) Algorithms: As mentioned earlier, we address here routing protocols for hierarchical sensor network topologies. One idea exploiting hierarchy in WSNs is designing a backbone made of particular nodes, use only the links within this backbone at one level of the hierarchy, and use direct links from other nodes to the backbone at another level. The backbone has to form a connected dominating set. Another idea for a hierarchy is to identify particular nodes which would have a special role, for example, controlling nodes in the neighborhood. In clustering techniques, these nodes are called cluster heads and they also have the role of aggregating traffic coming from neighboring sensors. Clustering is generally two-layered: inside a cluster, nodes communicate information to cluster heads and between clusters, cluster heads communicate information to the base station. An extension to more layers is obvious. Extended approaches use several cluster layers, which is called hierarchical clustering. Some other approaches propose group or grid nodes organization with the same objective, that of saving energy.

The algorithms used in the routing protocols over these architectures are generally responding to two questions: what is the view on the network needed for the algorithm, and what are the main metrics employed?

c) Evaluation: Different routing algorithms are generally difficult to compare because of the lack of standard testbed platforms or of the differences between evaluating parameters definition. We identify two main features in the routing protocol evaluation process: the experimental platform (testbed) and criteria used to evaluate the protocol.

The taxonomy parameters are resumed in figure 1.

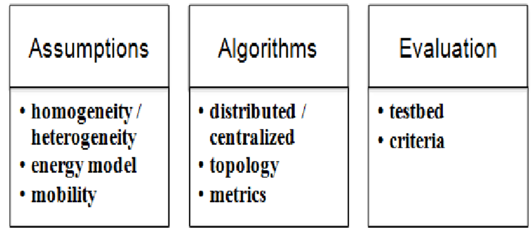

Fig. 1. Parameters for the WSN hierarchical routing protocols taxonomy

III. Assumptions

Determining the hypothesis on the wireless sensor network is of major importance for the design of an efficient routing protocol. We identify three assumptions generally made on this kind of networks: the energy model, the heterogeneity/homogeneity of the network and mobility of nodes.

Energy model In wireless sensor networks, energy consumption may be due to either computation (processing query request), or communication between sensors (forwarding queries to neighboring nodes, idle listening to the media, retransmission due to packet collision, generating/handling control packets, receiving data). The relation between the energy consumption in communicating data and computing heavily depends on the particular hardware in use: one bit transmission is 1500 to 2700 more costly than computing a single instruction for Rockwell WINS nodes, between 220 and 2900 for MEDUSA II nodes, about 100 for Bluetooth transmitters [14]. Summarizing, one should focus on energy consumption when communicating in wireless sensor networks, rather than computing, even though the latter cannot be ignored.

When transmitting information, two possible power scenarios exist:

- sensors can dynamically adapt its transmission power to achieve acceptable signal-to-noise ratio (SNR) at the receiver. In this case, the transmission energy per bit grows polynomially, in a quadratic form with respect to the transmission distance;
- sensors transmit at a fixed power level, if there is limited capability for dynamic power adjustments. Consequently, data between two sensors not within each other's radio range is forwarded by other sensors in the network.

Among approaches of hierarchical routing protocols presented here, most of them (CMLDA, Hierarchical PEGASIS, VGA, energy*delay approach, HEAD, HPAR, Top-Down) are based on hypothesis of dynamic power adjustment, and use the energy model presented in LEACH [3]. In LEACH, the radio is assumed to dissipate E_{elec} = 50 nJ/bit to run the transmitter or receiver circuitry and the transmission amplifier dissipates ϵ_{amp} = 100 pJ/bit/m^2 in order to achieve an acceptable signal to noise ratio (SNR) (see figure 2).

Thus, to transmit a k-bit message over a distance d using LEACH radio model, the radio expends: $E_{Tx}(k,d) = E_{elec} *$

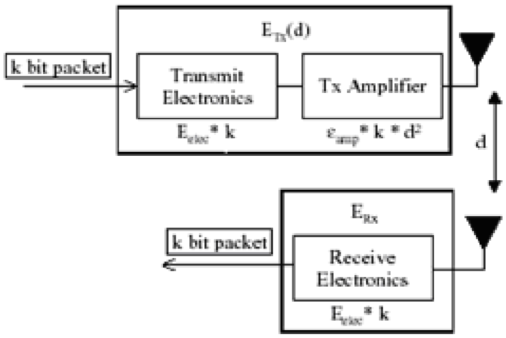

Fig. 2. LEACH radio model

$k + \epsilon_{amp} * k * d^2$ and to receive a k-bit message, the radio expends: $E_{Rx}(k) = E_{elec} * k$. For these parameter values, receiving data is not a low cost operation. PEGASIS mentions one scenario (using a 2000-bit packet and d^2 equals 500m^2) in which the energy spent in the amplifier part equals the energy spent in the electronic part, which makes transmission cost twice the reception cost. HPAR simplifies the LEACH energy model taking into account only the distance factor when computing the energy consumption in transmitting data to another node which is d distance away: $e = k * d^c$, where k and c are constants for the specified WSNs (usually c is between 2 and 4). HEED models the energy consumption in a more general way, based on a constant distance depending on the environment (by varying the ϵ_{amp} and the exponent of the distance in the transmission energy consumption formula). Other projects are less precise over their energy model, but make however energy assumptions for communications. In APTEEN, the base station is assumed to have adequate power to transmit directly to sensor nodes, while sensor nodes cannot always do this, because of their limited power supply. Multi-level clustering needs cluster head at increasing levels in the hierarchy to transmit data over relatively large distances. SOP mentions that the energy expended on transmission is proportional to the square of the distance between the sender and the receiver, and no particular assumption is made on the energy spent when receiving packets. They outline the known fact that the power consumed in N short hop transmissions is approximately N times smaller than the power consumed in one long hop transmission, so using short multi-hop communications rather than long-range ones may help in reducing power consumption. Particular assumption is done in the Hierarchical Clustering approach: sending or receiving have the same cost.

One more hypothesis concerning communication in WSNs refers to the energy-based symmetry of communications: the energy required to transmit a message from node A to node B can be the same as the energy required to transmit a message from node B to node A (which is called energy-based symmetric communication). When these energy consumptions are different the communication is energy-based asymmetric. LEACH, PEGASIS make the assumption that the radio channel is symmetric in respect to the energy consumption while APTEEN uses asymmetric energy-based communications.

Another strong assumption is that the communication environment is contention and error free; hence, sensors do not have to retransmit any data. This assumption may only be assured by an improved MAC layer, which loses generality of sensor architectures.

Heterogeneity in wireless sensor networks with respect to routing protocols is only present in one project, SOP, among the studied approaches. The different roles affected to network nodes make the SOP networks heterogeneous at software level. Some special sensors are used for monitoring climatic parameters. Other nodes have the functionality of relaying data, making thus the dissemination of information in the network. Software heterogeneity (through functionality of sensors) may be coupled with heterogeneity concerning the sensors' hardware. Some particular hardware is generally expected on sensors in most projects (SOP, APTEEN, CMLDA, PEGASIS, HPAR, TTDD, VGA, energy*delay), which help to determine node location (using GPS or other similar techniques). We are not classifying these approaches as heterogeneous because all nodes are supposed to be equipped with this hardware.

Mobility In most WSN applications, the sensors' locations are fixed and the instability during communication due to mobility of sensors is not an issue. However, mobility in WSNs can also exist, in given circumstances. The most frequent mobility concerns the sinks, nodes to which information should be delivered. It is the case of TTDD. Some more rare case is the assumption of SOP, where data discovery nodes are mobile, while the infrastructure needed for data dissemination is fixed.

IV. Hierarchical routing algorithms

Structuring wireless sensor networks is one of the main tools to save energy in each node of the network which results into prolonging the lifetime of the system. One of the most common architectures is the hierarchy. Hierarchical routing protocols in WSNs are based on different topologies. Such protocols, like SOP, use group infrastructure. A group is a subset of nodes collected with respect to specific parameters (distance between nodes, connectivity of a node, data collected, etc.). When the geographical position of the node is used to form the groups, we define zones (or grids). HPAR, VGA and TTDD are zone-based (or grid-based) protocols. LEACH, APTEEN, CMLDA, Hierarchical Clustering, and HEED form clusters which are groups of nodes with a cluster head in each cluster. The cluster head has an additional role of aggregation of received data from the other nodes. Another structure for hierarchic organization is the chain. In chains each node will receive and transmit data to a close neighbor. Hierarchical PEGASIS is a hierarchic protocol based on chains. The energy*delay approach combines the chains and the clusters. The cluster heads form the elements of the chain. Figure 3 classifies different topologies for WSN hierarchical protocols. Next, we briefly describe each approach and the routing metrics involved.

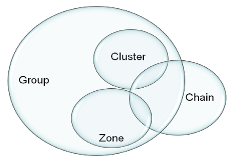

Fig. 3. Wireless Sensor Network infrastructures for routing protocols

Generally, hierarchical routing protocols act in two steps: structuring the network topology and applying the routing algorithm. The first step tends to build the hierarchy. The second one defines the rules and the strategy for transferring packets between nodes.

In SOP protocol, after group formation, a hierarchical tree is formed in order to create a routing table in each node of the network in a distributed manner. Two metrics are used for the routing. The first metric is the minimum energy consumption per bit of transmitted information. Using a second metric, the transmission is always done along the path that has the maximum capacity measured in terms of bits that can be transmitted. In LEACH, which is cluster-based, the routing of the data packets is achieved in two steps: the sensor nodes in the cluster send the sensed data in one hop to their own cluster head which forwards it directly to the base station. Therefore, routing in LEACH is done in a two-hop communication, one communication link being used inside a cluster, and one other communication link being used between the cluster head and the base station. Top-Down is also a distributed clustering approach. Cluster heads form a hierarchy; moreover, cluster members may also be included in this structure if their cluster heads are not directly reachable from any other cluster head in the hierarchy. APTEEN is similar to the Top-Down approach with a difference that the hierarchy is made only of cluster heads. HEED assumes single-hop communications among cluster heads and their registered cluster members. Cluster head overlay (i.e. inter-cluster) routes are used to communicate among clusters, or between clusters and the base station. In this case, an ad-hoc routing protocol, such as Direct Diffusion or Dynamic Source Routing (DSR), can be employed for data forwarding among cluster heads.

The centralized approach HPAR uses the max-min zPmin algorithm to find the path with the minimal power consumption in the zone. Each zone has a certain power estimation which is used to find the global path between zones using modified Bellman-Ford algorithm. The second objective is to maximize the minimal residual power. To send a message across the entire area, a global path from zone to zone is found. Each message is routed across the zones using information about the zone power estimation. A zone graph is used to represent connected neighboring zones. In order to route packets, TTDD uses geographical forwarding in a distributed way. The geographic forwarding exploits location information for packet delivery which requires GPS information, grid coordination, etc. It uses multi-hop transmission. Routing can be adapted to dynamic network architecture and has neither route establishment, nor per-destination state. Using the grid, a base station can flood a query, which will be forwarded to the nearest dissemination point in the local cell then the query is forwarded along other dissemination points up-stream to the source. The requested data then flows down in the reverse path to the sink. Trajectory forwarding is employed as the base station moves in the sensor field.

The energy*delay is a distributed cluster-based and chain-based approach. The base station determines the routes and creates routing schedule. For intra-cluster routing, the Shortest Path Algorithm (Dijkstra) determines the best route depending on energy, distance and connections. For inter-cluster routing, the cluster heads form a chain which is used to forward data to the base station. Hierarchical PEGASIS is also a chain-based approach. They consider sensor networks with nodes capable of CDMA communication, in which nodes that communicate use distinct codes to minimize radio interference. A linear chain is constructed among all nodes. For gathering data in each round, each node transmits to a close neighbor in a given level of the hierarchy. This occurs at every level in the hierarchy, but the only difference is that the nodes that are receiving at each level are the only nodes that forward to the next level. At the top level the only node remaining will be the leader, and the leader will send the message to the base station. For nodes that do not support CDMA, they suggest a 3-level chain-based scheme for data gathering. In this 3-level scheme, they start with the linear chain among all the nodes and divide them into 10 groups. Therefore, in a 100-node network, only 10 transmissions take place simultaneously, and data fusion takes place at each node (except the end nodes at each level).

In CMLDA, the authors are focused on constructing, via a centralized algorithm, aggregation trees such that the minimum residual energy among n sensors is maximized. Therefore, they do not specify any routing metrics. It is also the case of VGA which is a distributed algorithm. Another distributed algorithm, Hierarchical Clustering, assumes that a routing infrastructure is in place without mentioning any routing protocols.

V. Evaluation

One of the challenges in performance evaluation of routing protocols in WSNs is the lack of realistic evaluation model that allows researchers to test and compare works. Some current parameters that are used to evaluate performances of routing protocols, and also of hierarchical ones, are **network lifetime** and **energy consumption**.

In literature [15], there are many definitions for the lifetime of a network, but the most common one is the time until the first (or last) node in the network depletes its energy. Defining when a node is ”dead” may also slightly vary: energy*delay approach considers a node has been drained of its energy when the energy level reaches 0, while HEED considers a node dead if it has lost 99,9% of its initial energy. Almost all analyzed approaches estimate this parameter in slightly different forms.

HEED considers the network lifetime in a context of multi-hop networks, directly dependant on network connectivity. The network lifetime in multi-hop networks is defined as the time until the first (or last) node in V' depletes its energy, where V' is a subset of nodes that can reach the base station in one hop (full-duplex). HPAR computes the network lifetime by the earliest time a message cannot be sent, CMLDA and energy*delay by the number of rounds before the first sensor is drained of its energy, APTEEN by the total number of nodes alive (which gives also an idea of the network area coverage over time).

Another important factor in analyzing the routing protocols is the dissipated energy metric. LEACH, TTDD, Hierarchical Clustering, energy*delay and Top-Down estimate the energy consumption in network communications (when transmitting and receiving). In APTEEN, energy saving is achieved by discontinuously data transmissions; the total number of data signals received at the sink help estimating the network lifetime.

Two more evaluation criteria are important to discuss: one concerning especially the routing mechanisms, is the overhead (TTTD, energy*delay - the total number of header bits transferred from sensors, HEED - the energy consumed for routing updates, clustering and packet forwarding, SOP - the cost of broadcasting messages), and the other concerning especially the topology on which communication is made, is the delay (APTEEN, PEGASIS, TTDD, energy*delay).

When investigating routing protocols in wireless sensor networks, researchers are using different methodologies and tools: graph network modeling, simulators and real life platforms.

Traditional wireless routing algorithms model a wireless network as a graph in which edges define links between nodes. This model helps to consider edges as "tunnels" between nodes. In wireless networks, graphs must be interpreted as connecting all nodes which are within the transmission range of each other. In other words, an edge exists between two nodes if and only if these two nodes experience enough SNR. The interference range is usually not modeled in the graph, which is another drawback of this method. These aspects together with the numerous parameters which need to be considered and complex interactions which occur, make network graphs an incomplete modeling method. Simulators belong to the class of high level observation tools. Based also on models, more complete than the graphs, simulators have their own drawbacks: large scale systems need a lot of resources to be simulated, real world phenomena can difficultly be integrated in the model, some researchers point out the question whether the model reflects the reality. Real life experimental platforms may solve previous problems by running the real software on realistic hardware. The main limitation of real life platforms are their scalability and their intrinsic dependency on a specific set of real life conditions. Thus, results obtained on real platforms are hardly representative of the ones run on other platforms.

The difficulties of having real testbed platforms can obviously be understood for routing protocols evaluation which generally concerns large scale WSNs. Our analysis shows one single real platform (on which the evaluation of the clustered multi-hop routing - iHeed - was done) at quite reduced scale (6 Mica2 and 4 Mica2Dot sensors distributed over an area of about 18 feet $\times$ 12 feet). Most protocols are evaluated on the basis of simulators (NS-2 for APTEEN and TTDD, MATLAB for LEACH and Hierarchical Clustering, SENSE for PEGASIS and energy*delay, TOSSIM for Top-Down), while quite few use graph modeling (SOP, CMLDA, VGA, HEED).

VI. Global taxonomy view

In this paper, we encompass some published work in the field of wireless sensor networks, focused on hierarchical routing algorithms. We propose a taxonomy, aiming to provide a unified view of these approaches. Three parameters are identified in order to draw up the classification: the assumptions on the wireless sensor network, the algorithms forming the infrastructure and involved in the routing protocols, and the evaluation of these algorithms.

Energy efficiency is a key design objective in most research related to WSNs, routing protocols included. This justifies the need to judiciously identify the energy model of the considered network (particularly the energy a sensor expends on communication). A second influence on energy consumption is the heterogeneity of the system (either software or hardware). Heterogeneous systems do not drain batteries uniformly per node basis, unlike homogeneous ones, due to different functionalities of sensors or to particular hardware embedded. One more important factor that depletes energy is nodes mobility, feature which generates more topology control messages. All these factors build up the three types of the first taxonomy parameter, the assumptions: the heterogeneity/homogeneity of the system, the energy model, the mobility (see figure 4 for project classification based on these parameters' values).

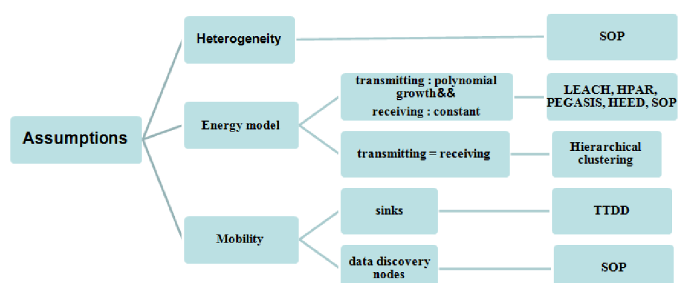

Fig. 4. WSN hierarchical routing protocols taxonomy: assumptions parameter

Figure 5 shows the routing metrics for each approach. It is clear that each approach defines its own routing algorithm that depends on the infrastructure. Figure 6 shows the classification of WSN hierarchic routing approaches based on the network topology. Structuring approaches have an infrastructure as defined in figure 3 and are either centralized or distributed. Centralized approaches are managed by the base station.

SOP	• Path having the minimum energy consumption per bit • Path having the maximum capacity
PEGASIS	• With CDMA: linear chain • Without CDMA: 3-level chain-based scheme
HPAR	• Intra-zone : max-min zPmin algorithm • Inter-zone: Bellman-Ford
energy*delay	• Intra-cluster : Dijkstra • Inter-cluster: CHs form a chain
HEED	• Inter-cluster: one hop between CH and the cluster member • Intra-cluster : Ad-hoc routing protocol like DSR, DD.
LEACH	• Nodes communicate data to their CH • CHs communicate directly to the BS
Top-Down	• Hierarchy made of member nodes and CHs • Member nodes send data to their parents (CH or not)
APTEEN	• Hierarchy is made of CHs • Nodes send data to CHs which forward it to the BS via other CHs
TTDD	• Geographical forwarding
Hier Clustering	• An existing routing infrastructure is assumed
VGA	• Routing metrics are not specified
CMLDA	• Routing metrics are not specified

Fig. 5. WSN hierarchical routing algorithms: metrics

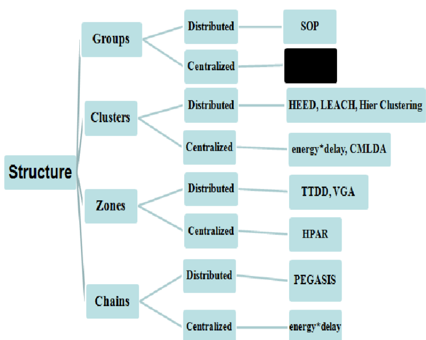

Fig. 6. WSN hierarchical routing protocols taxonomy: topology parameter

Routing protocols in hierarchical architectures are subject to evaluation, either on the basis of graph modeling, or using simulators. Real testbed platforms are quite rare. Two main metrics seem to be estimated for these protocols: network lifetime and energy consumption. These basic parameters (see figure 7 for project classification) may also be applied for the evaluation of routing protocols, independently of the infrastructure.

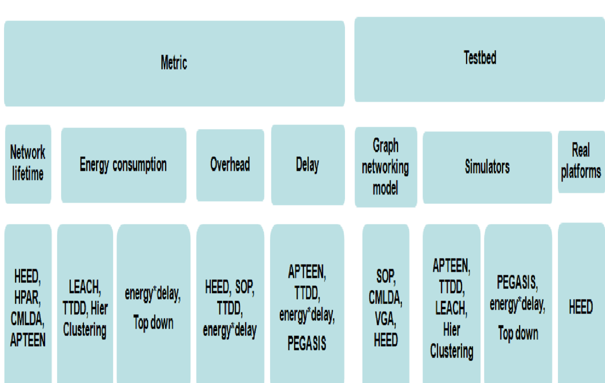

Fig. 7. WSN hierarchic routing protocols taxonomy: evaluation parameter

The utility of the presented taxonomy is providing comparison criteria of different WSN hierarchical routing protocols in literature and an approach for new designers of such protocols. Compared to Ibriq and I. Mahgoub's bibliography [16], the taxonomy we present tends to unify different points of view regarding cluster-based routing in wireless sensor networks and extend the approaches to other architectures, similar to clusters, works being thus complementary.

As in the case of any bibliography, there are many works to be considered. The exclusion of any particular result has been neither intentional nor should it be considered as a judgment of that work's merit.

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