Routing Protocols for Dense Wireless Sensor Networks: Characteristics and Challenges

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***Abstract*—Wireless Sensor Networks WSNs are emerged as effective network types which mainly depend on employing very small manufactured sensor nodes to aggregate the environmental data and then transfer it toward the concerned node. Some tactical applications such as medical, military, monitoring, emergency, and others require high density of WSN in limited area. Dense WSNs is a special type of WSNs in which very large density for the deployed nodes and also for the exchanged data are considered. Routing process in DWSNs requires special design due to its unique characteristics and requirements. This paper investigates the characteristics, design and challenges in routing protocols of DWSNs. Furthermore; the paper classifies the routing protocols based on different criteria. The paper ends up with an evaluation of several hierarchal and flat-based routing protocols based on different performance criteria. Finally some open research areas, conclusion remarks and future works are presented.**

***Index Terms*—Wireless Sensor Network (WSN); Routing protocol; Dense WSN.**

I. INTRODUCTION

A great revolution has occurred in the field of communication and networks. This revolution leads to continuous and increase requests for manufacturing very small and low costs electronic sensor devices, which in turn can be employed to perform the communication process within several tactical applications. Several numbers of these sensors are grouped to form "Wireless Sensor Network (WSN) [1]. WSN is considered significant and effective technology to be used by several applications through the last century. A great deal of attention is given to this type of networks from industrial and academic fields all over the worlds. The sensor nodes are characterized with low power, low cost and it could perform several functions starting from sensing to wireless communication [2]. The sensor nodes are permitted to perform the communication process among each other or directly toward the "Base Station (BS)" [1]. As shown in Figure 1; the sensor nodes are randomly distributed within sensor field without any careful engineering and planning processes. Furthermore; the nodes organize and direct themselves in order to generate critical information related to the sensor field's physical environment. The sensor node decision is based mainly on the current information available for this node and the node knowledge about the energy, communication and computing resources [1], [2].

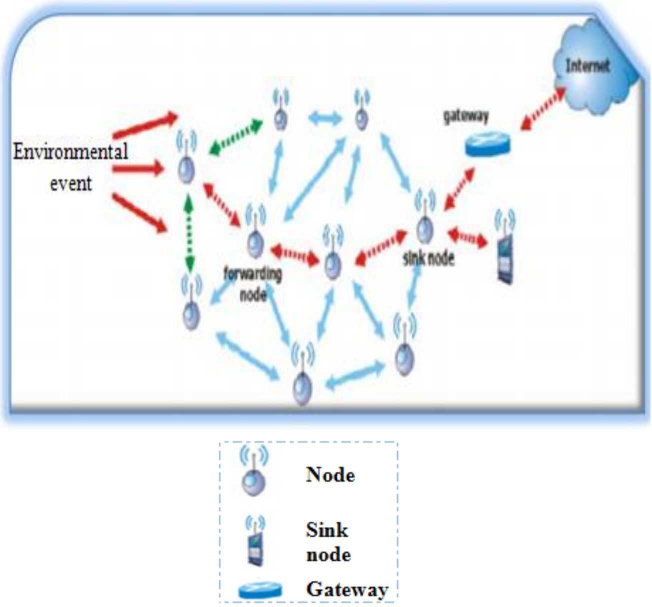

Figure 1: Wireless sensor network [3]

"Dense WSN (DWSN)" is a type of WSNs in which the nodes are deployed into denser way and the amount of exchanged data between the sensor nodes is very large. A great deal of importance and attention is currently given to DWSNs since it is commonly deployed to be used within several tactical applications [4].

II. CHARACTERISTICS OF DWSNS

DWSNs characterizes with the following constraints and characteristics [2], [3], [5];

i. Dense Deployment for the sensor nodes; the deployment of the nodes is very dense inside the sensor filed and typically it is higher than this occurred in ordinary cellular networks or in "MANETs".
ii. Sensor nodes are powered through batteries; the nodes are fed with batteries of constraint energy that is usually not an easy task to recharge or replace.
iii. Self-configurable; the distribution for the nodes within sensing filed is performed randomly.
iv. Strict energy, storage and computation constraints.
v. Sensor nodes are unreliable; this is because the nodes are probable to fail or damage since it is deployed within harsh environment.
vi. Redundancy of the data; in most DWSNs applications, the nodes are distributed densely, nodes

also work together in order to perform a specific sensing task. As a result; there is redundancy and correlation levels gathered by several nodes within the network.

vii. Design for specific application; DWSNs are designed usually for precise application where the requirements of the design are varied.

viii. “Many-to-one traffic pattern”; the sensed data flows from several sensors toward a specific sink, this results in a traffic pattern called “Many-to-one.

ix. Changeable topology for the network; the topology of DWSN is prone to change anytime due to failure of the nodes, depletion of the energy, channel fading, node addition and damage.

III. APPLICATION AREAS OF DENSE WIRELESS SENSOR NETWORK

New researchers have been attracted by DWSNs towards the design of new applications. Putting in mind the rapid development of number of application, it is not easy to put together an exhaustive list of sensor network applications, while some intended applications of DWSNs are still under research and development [6]. DWSNs applications can be classified into three categories (as shown in Figure 2):

i. Monitoring space;
ii. Monitoring things;
iii. Monitoring interactions of related things with each other and surrounding space.

Space monitoring involves several aspects as environmental [7] and habitat monitoring [8], home automation [9], precision agriculture [10], indoor climate control, surveillance, treaty verification and intelligent alarms. Whereas monitoring things includes eco-physiology, condition-based equipment maintenance, structural monitoring, medical diagnostics and urban terrain mapping. Also, the most dramatic applications of DWSNs contains disaster management, monitoring complex interactions, including, asset tracking, response to emergency, manufacturing process flow and healthcare [7]. Details of some major applications are briefly described below:

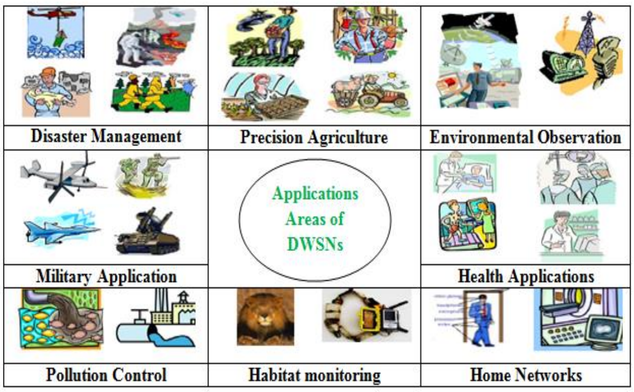

Figure 2: Applications areas of dense wireless sensor network

A. *Military Application*

DWSNs can improve coordination and planning of military applications by providing real time information of the enemy activities to military teams. The decision-making and sensing, monitoring should be combined perfectly. The timely collection and accurate visual surveillance and intelligence data can minimize the loss of human lives as well as play a central role in achieving objectives as well [9].

i. Battlefield Surveillance: Critical terrains, approach routes, paths can be covered with sensor networks. By using its data activities of opposing forces can be watched.

ii. Monitoring Friendly Force Equipment and Ammunition: Commanders can monitor the latest condition of its own force by using DWSNs. Each vehicle, equipment and ammunitions are attached with a sensor which sends current status to the sink node.

iii. Nuclear Biological and Chemical Attack Detection: DWSNs can be deployed in friendly region and it can generate an alarm when it detects any Nuclear Biological and Chemical Attack.

B. *Health Applications*

Monitoring doctor and patient are some health applications for sensor networks. Others are telemonitoring of human physical data, tracking, and drug administration etc. [11].

i. Telemonitoring of Human Physiological Data: DWSNs can be used to collect physiological data for long time period which can be used to detect predefined symptoms.

ii. Tracking and Monitoring Doctors and Patients inside a hospital: Every patient is given a small and light weight sensors attached to them. One sensor node may detect the blood pressure the heart performance while another is detecting the blood pressure etc.

C. *Environmental Observation*

Monitoring the environment can be terminated by DWSNs in cases such as rainfall observation in agriculture, flood detection, forest fire detection, air pollution detection, etc. Sensors can be used to locate toxic waste, illegally dumped into a lake and relaying the same origin of a pollutant to a central authority, that can take appropriate measures, to limit spread of the pollution. WSN, enabled the data collection without the nearby factory’s knowledge, as the factory may prevent the data gathering process [7].

D. *Disaster Management*

DWSNs has reliable early warning system which can be deployed in areas with high risk of disasters. Its usage provides real time information of the disaster area to rescue teams making planning and coordination more effective. As location information of victims, objects and rescuers in the disaster is vital for the rescue operations. To manage a disaster effectively: sensing, decision-making and monitoring should be integrated seamlessly [8].

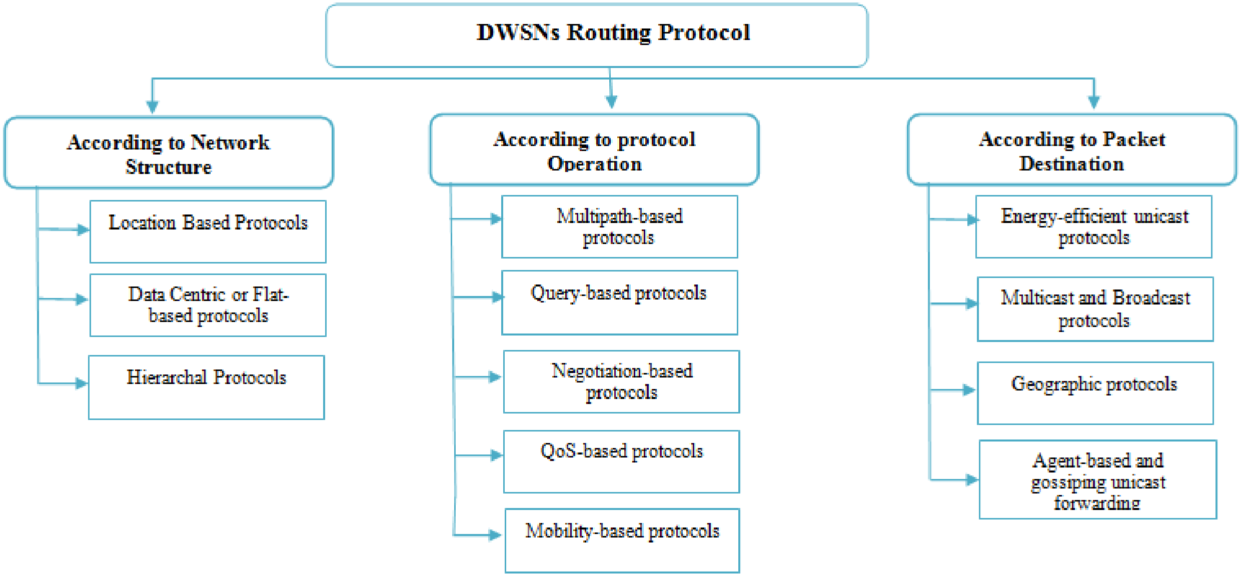

Figure 3: Routing Protocols Classification in DWSNs

IV. ROUTING IN DWSNS

A. *Introduction to Routing Process in DWSNs*

The process of routing within DWSNs differs from the usual routing in several aspects, such as; infrastructure-less nature of DWSN, unreliable wireless links, probable failure of sensor nodes and the requirements of energy saving that must be achieved by the routing protocol. Generally, there are several techniques of routing that were developed by the researchers during the last years. Actually; these protocols can be classified as illustrated in Figure 3.

Routing protocols are classified according to network structure, protocol operation and packet destination. Below is a simple clarification for mentioned sub-categories protocols [2], [12], [13];

i. "Location-based protocols"; addressing of the sensor nodes is performed based on their locations. The information of the sensor location is vital for DWSN via most routing protocols in order to compute the distance among two specific nodes and hence to estimate energy consumption.

ii. "Data Centric Protocols"; these protocols follow different manner for sending the data from the source toward the sink nodes. In address-centric type; the nodes send their data toward the sink. This process is performed independently from the remaining nodes. In data-centric type; the intermediate nodes between the source and sink aggregate data from several source nodes, then direct them to the sink node. As a result; number of transmission nodes needed to send data toward sink node is reduced hence less energy is required.

iii. "Hierarchal Protocols"; this type of protocols depends on dividing the whole DWSN into smaller areas called clusters. The clustering process is considered energy efficient algorithm to transmit data toward the sink node in hierarchal procedure. Each cluster has a "Cluster Head (CH)", which in turn manages and controls data exchange process between the ordinary nodes and BS.

iv. "Mobility-based Protocols"; the mobility issue within DWSN is considered new and critical challenge for the routing process. An efficient protocol in terms of energy is required in case of the mobility of the sink node in order to ensure the delivery of data from source to sink nodes.

v. "Multipath-based protocols"; two paradigms are available to perform data transmission from source to sink nodes, which are; single and multipath routing. In single-path routing; the data is sent from source nodes toward sink node through the path with shortest distance. In multi-path type, the sensors discover k number of paths characterized with shortest distance to the sink node. The load is then divided and eventually distributed between the selected paths.

vi. "Heterogeneity-based Protocols"; within heterogeneity type of DWSNs; there is two sensor types; line-powered and battery powered sensors. Battery-powered type is characterized with restricted lifetime while the line-powered type has no constraint of energy. As a result, battery-powered sensor types must utilize the obtainable energy in effective procedure via reducing data computation and communication processes as much as possible.

vii. "QoS-based protocols"; QoS is considered essential parameter in DWSNs, in addition to the constraint of energy. The QoS is mainly measured in terms of reliability, tolerance of fault and delay.

viii. "Query-based protocols"; the inquiry for the data is propagated by destination node throughout DWSN. The sensor node that own the required data accordingly responds to the query message by transmitting it toward the destination node.

ix. "Negotiation-Based Protocols"; data descriptors with high level is employed in these protocols to get rid of data redundancy during transmission via employing the negotiation strategy. Furthermore; the decision of communication is performed according to the obtainable resources.

x. Agent-based and gossiping unicast forwarding; in this type of protocols, it tries to get rid of routing tables as a way of reducing the overflow. The implosion problem is avoided via gossiping, selecting node randomly and sending the packet toward it instead of blind broadcast of the messages. Propagation delay will be the cost.

- xi. Energy-efficient unicast protocols; in these protocols, the distribution of nodes within the network is analyzed in order to determine the transmission cost among two nodes and then employ an efficient algorithm in minimum cost calculation.
- xii. Geographic protocols; two major motivations are beyond these protocols; the location of the node is required by several applications as reference address in order to permit “the closer node to appoint” or “every node in a given region” destination types. This is known as geo-casting. The second motivation is when the destination and source positions are recognized in addition to the nodes between them, which can be effectively employed. This process is called “position-based routing”.
- xiii. Multicast and broadcast protocols; broadcast is familiar process within WSNs, in which the data is distributed to all nodes inside the network. Another common approach is multicast, in which data is distributed by one node to set of specific nodes within the network.

B. Routing Challenges and Design Issues in DWSNs

There are two primary challenges in DWSN. First, the huge amount of data produced by sensor nodes which can commonly increase to a several thousands. Second, the higher packet latency from one node to another and the increasingly higher energy consumption utilized by sensor node radio transceiver for transmitting data to the sink. Because the sensor nodes have very limited energy resources where some sensors use non-rechargeable batteries, increased energy consumption is key challenge in DWSN. With exhausted energy resources the lifetime for DWSN reaches an end because inability of sensor nodes to operate. DWSN must reduce costs for sensor nodes to the minimum which reduce the memory and processing power causing performance challenges. At the same time, cost is not the only decisive factor because high processing power is not feasible due to energy efficiency requirements.

Routing challenges include dealing with lack of backbone infrastructure for routing information and topology definitions, lack of bandwidth limitations, low memory foot print on sensor nodes for packet message header data, routing overheads due to idle listening, occurrence of collisions during route discovery leading towards reduced energy efficiency and the challenge to be resilient to ensure network operation where some nodes fail [13]. Some of the routing challenges and design issues are as following,

Network Dynamics: The key components are sensor nodes, monitor events and sinks or cluster-heads (gateways) which influence the route optimization and in turn the energy consumption. Network design considerations and protocol application depends greatly on the ‘event’. The event could be either dynamic or static based on the intended use of the DWSN. Static events require less often reporting while dynamic events require reporting in more often occurrence thus generates significant traffic to be routed and also prevents increased idle wait or node sleep/wakeup techniques [14].

Node Deployment: Node deployment in DWSN influences the performance of routing protocol. Node deployment could be either deterministic or self-organizing where in first case nodes are installed with pre-determined routing paths while the later approach creates an ad-hoc routing path in often a scattered settings. The routing path is determined using route path discovery techniques like flooding. Node deployment is a deterministic characteristic for performance, energy efficiency, selection of routing technique and routing protocol [15].

Energy Considerations: Network deployments, routing paths and setting up routing protocol is directly influenced by energy considerations. Often multi-hopping is more energy efficient as compared to direct routing but with increased overhead and other performance issues. Multiple factors contribute towards energy consideration also determine the life span of the sensor node [16].

Data Delivery Mode: To ensure the route stability and energy efficiency in DWSN data mode highly influences the routing protocol. Data delivery modes are query driven, event driven, continuous and hybrid, each with different requirements. Also, it determines data aggregation and redundancy techniques [17].

Node Capabilities: Sensor nodes often possess equivalent capabilities in terms of memory for routing packets, computational power, communication power, and battery capacity for operation of the nodes. Sensor nodes perform data relaying, sensing and aggregation activities simultaneously which drain the battery power more quickly. Some hierarchical protocols are proposed with different cluster heads optimized techniques in order to increase energy efficiency [18].

Data Aggregation: Role of redundancy is two-fold in DWSN. It is both a requirement for stability and reliability. Also, redundant data causes energy efficiency and performance considerations. Data for redundant packets could be aggregated for decreased traffic and improved energy efficiency. [19].

Common techniques to address the above challenges are done by putting nodes into sleep/wakeup cycles as long as possible in order to reduce idle listening overheads and improve energy efficiency. Multiple channels, channel hopping and real time operating systems are used for improved performance. Low power listening, stretching preamble of message and providing ability of packet sender to wakeup receiver, minimizing idle listening and reducing duty cycles ensure higher power efficiency. Routing protocols adhering towards DWSN ensure collision free communication by using flooding only for route detection, and use algorithms for shortest routing path detection.

During this paper only flat based and hierarchal based routing protocols will be considered. An investigation for the process and concepts for each category will be detailed. A comparative evaluation study is then introduced for set of hierarchal and flat based routing protocols in terms of several criteria.

V. Flat-Based and Hierarchal Based Routing Protocols in DWSNs

Sensor nodes within DWSNs cooperate the communication process in order to finally transfer data toward a central node called sink. The nodes may also perform a specific coordination for data like or data fusion. These sink nodes are permitted to access Internet and hence user obtains required data. Figure 4 illustrates two common and probable topologies for data transmission; flat-based and hierarchical routing [13].

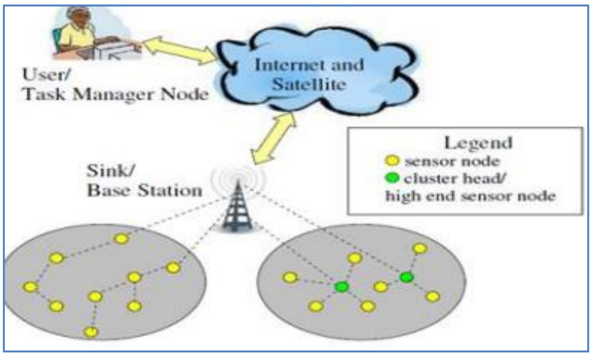

Figure 4: Hierarchal and Flat-Based Routing Topologies in DWSNs [13]

In flat-based routing process, all sensor nodes inside the network are considered as routers for the aggregated data and routing process. Clearly, any node can contact BS. Several benefits may be obtained as a result of applying this type of routing protocols in the network. These include saving energy, cutting the redundant data down, data could be horizontally or vertically transmitted, non-working nodes can be also eliminated where node position can be approximated employing radio waves. Differently, in hierarchical type of routing, nodes are either ordinary or CH nodes. The communication process is performed into different levels; in the first level the ordinary nodes transmit their sensed data toward the CH inside the cluster. The CH in turn transmit this data toward the BS. Hierarchical based routing is effective in reducing transmission inside the network since only the CH are permitted to contact the BS [13]. More than one level may be considered in hierarchical based routing. This in turn results in extending the network scalability, energy and lifetime. Lifetime of the network can be enhanced through decreasing traffic via performing data fusion and aggregation.

VI. Evaluation of Routing Protocols in DWSNs

Table 1 represents comparison between flat and hierarchal routing protocols in DWSNs. The comparison is based on their classification, energy efficiency, data aggregation, delivery, multipath, cluster overhead, network lifetime, and scalability.

Table 1
Comparison between flat-based and hierarchal routing protocols in DWSNs.

Routing Protocol	Classification	Energy Efficiency	Data Aggregation	Data Delivery	Multi-path	Cluster Overhead	Network Lifetime	Scalability	Performance in general
SPIN [20]	Flat	Good	Yes	Event Driven	No	Low	Limited	Limited	Limited
DD [21]	Flat	Good	Yes	Demand driven	No	Low	Limited	Limited	Limited
Rumor [22]	Flat	Good	Yes	Demand driven	No	Low	Limited	Good	Limited
GBR [23]	Flat	Good	Yes	Hybrid	No	Low	Limited	Limited	Limited
CADR [24]	Flat	Good	Yes	Continuously	No	Low	Limited	Limited	Limited
COUGAR [25]	Flat	Good	Yes	Query driven	No	High	Good	Limited	Good
ACQUIRE [26]	Flat	Good	Yes	Complex query	No	Low	Limited	Limited	Limited
LEACH [27]	Hierarchical	Bad	Yes	Cluster-head	No	High	Good	Good	Good
TEEN [15]	Hierarchical	Bad	Yes	Active threshold	No	High	Limited	Good	Good
APTEEN [28]	Hierarchical	Bad	Yes	Active threshold	No	High	Good	Good	Good
PEGASIS [17]	Hierarchical	Bad	No	Chains based	No	Low	Good	Good	Good
VGA [29]	Hierarchical	Good	Yes	Good	No	High	Limited	Good	Limited
SOP [30]	Hierarchical	Good	No	Continuously	No	High	Limited	Good	Limited
GAF [31]	Hierarchical	Good	No	Virtual grid	No	Mid	Limited	Good	Limited
SPAN [32]	Hierarchical	Good	Yes	Continuously	No	High	Limited	Limited	Limited
CCM [33]	Hierarchical	Good	Yes	Chains based	No	Low	Good	Good	Good
BCDCP [34]	Hierarchical	Good	No	Demand driven	No	Mid	Good	Limited	Limited
DAIC [35]	Hierarchical	Good	Yes	Demand	No	Mid	Good	Good	Good
DirQ [36]	Hierarchical	Bad	Yes	Continuously	No	Low	Limited	Good	Good
SHRP [37]	Hierarchical	Good	Yes	Continuously	Yes	Mid	Limited	Good	Good
HEED [38]	Hierarchical	Bad	No	Continuously	No	Low	Low	Limited	Good
PEGASIS [39]	Hierarchical	Bad	No	Chains based	No	Low	Low	Good	Good
IDD [40]	Hybrid	Good	Yes	Demand driven	Yes	Mid	Good	Limited	Good
DDBCI [41]	Hybrid	Good	Yes	Demand driven	Yes	Mid	Good	Good	Good

VII. Open Research Areas

The previous section introduces a comparison between several commonly used routing protocols within DWSNs. As listed in Table1, the protocols varied within their performance criteria and no one of them is optimum in terms of all selected criteria. So, selection of the routing protocol to be employed within the DWSNs depends mainly on the network design goals and objectives considering the tradeoff between the protocols as mentioned previously. Research issues in DWSNs fall into a lack of definition, and thus proposal for a standard protocol which ensures maximum achievement of potential energy efficiency, accuracy, reliability, scalability and performance. Lacking of QoS and energy efficiency aware routing protocols is also known to be open research area.

VIII. CONCLUSIONS AND FUTURE WORKS

To conclude, this paper revised and investigated the DWSNs definition, applications, routing and design challenges. The paper investigated the routing process inside this type of networks and illustrates different classifications based on several criteria. The flat and hierarchal-based routing protocols were discussed and their processes were analyzed. The paper then presented an evaluation for several hierarchal and flat-based routing protocols in terms of different performance criteria. The evaluation showed that no protocol is optimum in terms of all performance criteria and always there is a tradeoff depends on the design requirements and application.

Several points may be adopted in order to improve the routing process in DWSNs;

i. There is a need for further research to be conducted in some areas such as QoS and network scalability.
ii. There is huge potential for energy and performance aware DWSN routing protocol with higher QoS values.
iii. Hierarchal-based and flat-based routing protocols may be utilized to design a protocol that combine both routing processes in order to exploit their advantages as much as possible.
iv. An essential point that must be considered during the design for any routing protocol for DWSN is the balancing the routing performance as much as possible. This will not achieve better performance in terms of some criteria in the expense of others

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