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A Comparative Study and Analysis of Data Aggregation Techniques in WSN

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Abstract

Background: Wireless Sensor Network (WSN) often consists of large number sensor nodes which co-operatively send sensed data to base station. These networks are used in various applications scenarios such as habitat monitoring, disaster management, security and military, etc. As the sensor nodes are generally operated by battery driven, an efficient utilization of power is essential. Therefore, to enhance the life time of sensor network, power efficient methods has to be adapted to gather and aggregate data. It's mainly because majority of the sensor node energy is consumed during transmission than computation. Data aggregation is one of the widely recognized solutions to gather and reduce the redundant number of packets to be sent to base station by aggregating them. Literature survey shows that several application specific sensor network data gathering protocols exists in enhancing the network lifetime. **Methods**: This paper provides a comprehensive survey of different data aggregation algorithms in wireless sensor networks. The different algorithm are compared and contrasted based on the performance measures such as network type, mobility, Data (D) or Node (N) centric protocol, computation characteristics, data delivery model, communication pattern, query based support, energy usage and application type. To evaluate the performance of some of the algorithms surveyed in this work, simulation experiments on Matlab were conducted. **Results**: It was observed from the results that that the network topology has a high impact on the routing protocols to perform data aggregation. There exist few other protocols using contemporary methodologies such as Tree, Grid and Hybrid approaches which are also discussed in this paper. **Application**: The survey will help to identify the data aggregation algorithm suitable for a specific application.

Keywords: Data Aggregation, Energy, Lifetime, Network, Routing Protocol, Survey, Wireless Sensor Network (WSN)

1. Introduction

Wireless Sensor Networks (WSNs) are now-a-days used in various applications such as habitat monitoring, weather forecasting, antiterrorism, data gathering, intelligent control, traffic management and environmental observation[1]. The WSN consist one or more sensors, a processing unit with processing and program memory, a limited power supply, and a wireless transceiver to transmit the sensed data to sink node in the form of signals. The sensors can be deployed at specific locations or can be randomly scattered in places where the human intervention is less. These scattered sensor nodes has the capabilities to collect data and route data back to the sink node by a multi-hop infrastructure less architecture as shown in Figure 1.

During the multi-hop, energy conservation is the important factor in sensor network. An extensive quantity of energy is consumed when the data is send by its transceiver[2]. Therefore, it is necessary to reduce the

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number of packets transmitted among the network and to sink node. This can be done by combining the data at the intermediary node into high quality information before transmission. It results is energy conservation in the sensor nodes and efficient bandwidth utilization of the sensor network. In this context, data aggregation is recognized as an efficient technique for combining the data. It carries out the process of aggregating the data from multiple sensors, and provides the sink node with aggregated information[3]. Data aggregation achieves efficient bandwidth utilization by eliminating the redundant data getting transmitted. Another significant factor which influences data aggregation is, it delivers the most critical data in an energy efficient manner with minimum data latency[4].

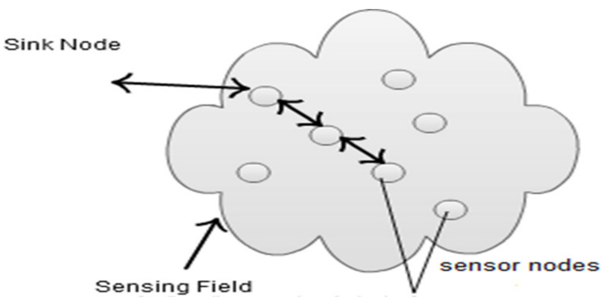

Figure 1. A typical wireless sensor network.

Therefore, to increase the network life time of the sensor network, designing an efficient data aggregation algorithm. However, the design of efficient data aggregation algorithms is an inherently challenging task. There has been intense research in the recent past on data aggregation in WSNs. Hence, in this paper a comprehensive survey of design issues and techniques for sensor networks describing the physical constraints on sensor nodes and the protocols proposed in all layers of network stack done. Then suggestions for suitable protocol for the sensor applications are also discussed. This survey provides a deep insight of the routing protocols. In addition, the different architectural design issues that may affect the performance of routing protocols are summarized.

The rest of the paper is organized as follows, in section 2, an extensive overview of basic ingredients of data aggregation is given. In section 3, several data aggregation algorithms based on network architecture are surveyed and studied. Section 4 gives a comparative analysis of the various aggregation methods. Simulation results are carried in section 5, to compare the performances of the various hierarchical data aggregation algorithm. Then in section 6, the data aggregation based on other protocols classification such as Tree, Grid, Hybrid and QoS are discussed. Finally, section 7 concludes.

2. Basic Ingredients of Aggregation

The three basic ingredients of aggregation techniques are routing protocols, aggregation functions and representation of data in wireless sensor network.

2.1 Routing Protocols

Routing protocols plays an important role in data aggregation[5]. The design of routing protocol for data aggregation deviate it from the traditional classical routing protocols. The main objective is to reduce the energy expenditure and the next hop to route the data to the sink node should be chosen to promote aggregation. This approach is referred as data-centric routing. The data forwarding is done based on the position of the most suitable aggregation points, the data type, the priority of the information, and so on[5]. There exists various data aggregation techniques based on the various routing protocols. One of the approaches is centralized data aggregation. It is an address centric approach, where the data from each node is sent to a central node via the shortest possible route using a multi-hop wireless protocol. The sensor node identifies a leader in the network and sends the data packets to it, which is the powerful node among all other existing nodes. The role of the leader is to aggregate the data which can be queried by the user. However, it has some disadvantages like heavy time consumption, limited ability to meet user needs, inflexibility, increased dependence and vulnerability. Then the other one is a decentralized approach, there is no single centralized node. All nodes are connected to its neighbor node and each node performs the aggregation function locally among them. Thereby all gets equal priority to perform the aggregation function. This approach is more scalable and tolerant of dynamic changes and node failures. It is also called as multi data aggregator model. Finally, the in-network approach uses a multi-hop mechanism to aggregate the data at the intermediate node.

2.2 Aggregation Functions

It is the most important functionalities that aggregation techniques should provide is the ability to combine data coming from different nodes[6]. There exists several aggregation functions and are closely related to the specific sensor application. Nevertheless they are based on some common paradigms such as lossy/lossless aggregation functions and duplicate sensitive/insensitive aggregation functions. Both lossy and lossless aggregation function compresses and merges the data. The main difference is, in lossy aggregation, is the original values cannot be recovered and accuracy of the data is lost in transmission. In contrast, in lossless the weakness of lossy aggregation is overcome. In certain cases, the intermediate node may receive redundant information. It can be handled by duplicate sensitive/insensitive aggregation functions. If the result of aggregation function depends based on the redundant data, duplicate insensitive aggregation is used, otherwise duplicate sensitive is used.

2.3 Data Representation

The sensor nodes has limited storage capabilities[7], therefore all the received/generated information cannot be stored. The node has to decide whether to store, discard, compress, or transmit the data. For performing this task the data has to be represented in an appropriate format. The format varies based on the application requirement. Generally, the data structure is common to all nodes, but the main constrain is it should be adaptable to node-specific or location specific characteristics. The distributed source coding technique is the recognized as promising method to deal with data representation and compression in the energy constraint sensor nodes.

3. Classification of Data Aggregation Protocols

The performance of the various data aggregation protocols is mainly influenced by the network architecture[8]. The classification of the different architectural attributes of sensor networks is illustrated in[8,9]. This work gives a high level description of what is considered typical sensor network architecture along with its components. Therefore the aggregation methods proposed based on the network architecture are discussed. In general, they can be classified as structured, structure-less and other types of network architectures. In structured aggregation, it uses specific architecture for performing data aggregation. The architecture is majorly classified as flat and hierarchical and location based aggregation as depicted in Figure 2.

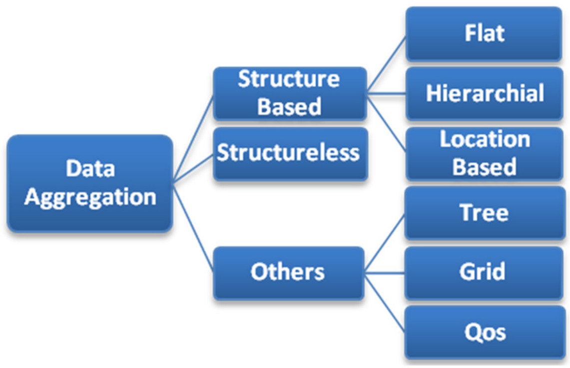

Figure 2. Types aggregation methods.

3.1 Structured-Based Aggregation

3.1.1 Flat Approach

In flat networks, all the sensor nodes typically plays the same role and sensor nodes collaborate together to perform the sensing task. Data aggregation adopts a data centric routing and query based approach. For instance, in flooding the base station broadcasts a query to all the sensor nodes in the network. The node that has the matching data with the query, it transmits the response back to the base station. The multihop path through which the data gets transferred is used to perform data aggregation. Thereby the latency of the network is very high. Some of the examples of routing protocols performing data aggregation in flat networks are flooding, gossiping, *Sensor Protocols for Information via Negotiation (SPIN)*[10], *Directed Diffusion (DD)*[11], *Rumor Routing (RR)*[12], *Gradient Based Routing (GBR), Constrained Anisotropic Diffusion Routing (CADR)*[13], *COUGAR*[14] *and A Ctive Query forwarding In sensoR nEtworks (ACQUIRE)*[15]. The drawbacks of flat networks are the scheduling of routes for data aggregation based only on contention and the aggregation of data is done only in the specific region (sink node) to which the data has been transmitted. It increases the computation overhead on sink node leading to faster energy depletion. Incase if the sink node fails, the entire network will be collapsed which in turn increases the overhead also.

3.1.2 Hierarchical Approach

Hierarchical networks overcome of sink node in flat networks by fusing the data at intermediate or special nodes. It reduces the number of messages transmitted to the sink, thereby improving the energy efficiency of the network. The Hierarchical approach is further classified into cluster and chain architectures. The data aggregation using structure less does not use any kind of specific architecture. Here the communication takes place at any node to node in the network.

3.1.2.1 Cluster based Aggregation

This method uses clustering, node heterogeneity and reservation based scheduling. In cluster based aggregation, the network is assigns a cluster heads to perform data aggregation. The main objective of this approach is to perform energy efficient data aggregation in large size networks. Here, the sensor nodes transmit the data to the local cluster head and it transmits the aggregated data to the sink node, instead of directly transmitting to the sink node. The cluster head can also reach the sink node using multi-hopping or through long range transmission. This approach significantly reduces the inefficiency and energy consumption of the energy constraint sensor nodes in large size networks. Recently, several cluster based network organization and data aggregation protocols have been proposed. The overhead is increased at cluster heads of the network. Even if one of the cluster head fails, aggregation of data is done by the nearest cluster head. Sensor nodes communicate with the cluster head thereby decreasing the latency. Some implementation of cluster based protocols are *Low Energy Adaptive Clustering Hierarchy (LEACH)*[16,17], *Hybrid Energy Efficient Distributed Clustering Approach (HEED)*[18], *Clustered AGgregation Technique (CAG)*[19], *Threshold sensitive Energy Efficient sensor Network protocol (TEEN)*[20] *and Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN)*[21].

3.1.2.2 Chain based Aggregation

Chain based data aggregation is one of the hierarchical methods of aggregation which forms chain architecture. In this approach energy is evenly distributed and each sensor node can communicate with its neighbors and each gets turn to be the leader for transmitting data to the base station. Token passing approach is used for choosing the leader. Once the token is received, that node sends the data to the aggregator node finally reaching the sink station. It greatly overcomes the drawbacks of LEACH by eliminating the overhead of dynamic cluster formation and minimizing the count of transmissions and receptions. *Power-Efficient Gathering in Sensor Information Systems (PEGASIS)*[22] *is well-known protocol for chain based routing. Chain Oriented Sensor Network for Efficient Data Collection (COSEN)*[23], *Chain-Based Hierarchical Routing Protocol (CHIRON)*[24] are various other protocols based on chain based networks.

3.1.3 Location based Approach

In this approach, the addresses of the sensor nodes are identified based on the location. The nodes position is identified using the incoming signal strength or using the Global Positioning System (GPS). To reduce the energy consumption, the inactive nodes are assigned with sleep mode. The routing protocol based on local based approach is SPAN.

3.2 Structureless Aggregation

In Structure-less data aggregation, any structure is not maintained. It is very useful in event based applications where event region changes very frequently. If any node fails there is no need to reconstruct the structure. The major drawback of structureless data aggregation is making the routing decision for performing data aggregation. *Data-Aware Any cast (DAA)*[25], a Media Access Control (MAC) layer protocol for spatial convergence is the mechanism available for structure less data aggregation. This approach is efficiently used for event based applications and it follows a Randomized Waiting (RW) approach. In DAA, a source node sends the RTS packet to all of its neighbors with Request-to-Send (RTS) it also attaches the type of data it has sensed. After receiving the RTS only those neighbor nodes send Clear-to-Send (CTS) packet that have same type of data. After receiving the CTS from more than one neighbor, source node selects only one of them according to instantaneous channel condition. DAA is based on MAC layer any-casting where we have the situation to select only one next hop among many.

Table 1. Summarization on flat, hierarchical and location based data aggregation

Aggregation based Routing Protocol	Network Type Classification	Mobility	Data Centric Protocol	Computation	Data Delivery Model	Communication Pattern		Query based	Energy Usage (Relative)	Application Type
						Base Station to Network	Network To Base Station			
SPIN	Flat	Mobile	Yes	Decentralized	Time / Event Driven	AnyCast	Unicast	Yes	Limited	Habitat Monitoring
DD	Flat	Limited	Yes	Decentralized	Demand Driven	AnyCast	Reverse Multicast	Yes	Limited	Environment Monitoring
RR	Flat	Fixed/ Very Limited	Yes	Decentralized	Demand Driven	AnyCast	Reverse Multicast	Yes	Low	Habitat/ Environment Monitoring
GBR	Flat	Limited	Yes	Decentralized	Event/ Demand Driven	AnyCast	Reverse Multicast	Yes	Low	Health Monitoring
CADR	Flat	Fixed	Yes	Decentralized	Continuous/Time/ Event Driven	AnyCast	Reverse Multicast	No	Limited	Environment Monitoring
COUGAR	Flat	Fixed	Yes	Decentralized	Query Driven	AnyCast	Reverse Multicast	Yes	Limited	Environment Monitoring
ACQUIRE	Flat	Limited	Yes	Decentralized	Complex Query	AnyCast	Reverse Multicast	Yes	Low	Environment Monitoring
LEACH	Hierarchical/ Cluster	Fixed BS	No	Centralized -Cluster Head	Event Driven	AnyCast	Reverse Multicast	No	High	Health Monitoring
HEED	Hierarchical/ Cluster	Fixed BS	No	Centralized- Inter-Cluster	Event Driven	AnyCast	Reverse Multicast	Yes	Low	Environment Monitoring
CAG	Hierarchical/ Cluster	Fixed BS	No	Centralized - Cluster Head and Sender	Event Driven	AnyCast	Reverse Multicast	Yes	Low	Habitat Monitoring
TEEN	Hierarchical/ Cluster	Fixed BS	Yes	Centralized	Action Threshold	AnyCast	Reverse Multicast	No	High	Home/Office Monitoring
APTEEN	Hierarchical/ Cluster	Fixed BS	Yes	Centralized	Event Driven	AnyCast	Reverse Multicast	No	High	Home/Office Monitoring
PEGASIS	Hierarchical/ Chain	Fixed BS	No	Centralized - Chain Leader	Event Driven	AnyCast	Unicast	No	Max	Disaster Monitoring
COSEN	Hierarchical/ Chain	Fixed BS	No	Centralized- Muti-level Chain Leader	Event Driven	AnyCast	Unicast	No	Low	Battlefield Monitoring
CHIRON	Hierarchical/ Chain	Fixed BS	No	Centralized -Fan Shaped Group - Chain Leader for each group	Event Driven	AnyCast	Unicast	No	Low	Civil/Military Monitoring
SPAN	Hierarchical/ Location	Limited	No	Decentralized	Continuous	AnyCast	Reverse Multicast	No	High	Civil/ Military/ Habitat Monitoring

DAA improves the performance of data aggregation in comparison to structured approaches. If the DAA is used with the RW, it further improves the performance.

4. Comparison of Data Aggregation Approaches

Table 1 summarizes the classification of the aggregation supported routing protocols covered in this survey. These protocols is an important consideration in terms of energy saving and traffic optimization. Therefore, to choose the most appropriate data aggregation protocols for a sensor application, these methods are classified according to vital characteristics. Using this classification, the application designer can choose the most appropriate method for the application. The various characteristics taken for classification are network type, mobility, Data (D) or Node (N) centric protocol, computation characteristics, data delivery model, communication pattern, query based support, energy usage and application type.

- **Network Type:** The data aggregation protocol is classified under which type of network classification**.**
- **Mobility:** The position of base station in the aggregation methods. It can be either fixed (stationary) or mobile.
- **Data Centric Protocol:** The protocols designed for WSNs are more data-centric. In data-centric routing, the sink sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute based naming is necessary to specify the properties of data. Here, data is usually transmitted from every sensor node within the deployment region with significant redundancy.
- **Computation:** The nodes store the identification of their neighbors, in centralized or decentralized manner.
- **Data Delivery Model:** The delivery model describes what initiates the data reporting process.It is distinguished as time-driven, query-driven, and event-driven protocols. *Time-driven:* Employing a time-driven routing protocol, a sensor node is triggered in specific moments, when it should perform its measurement task and forwards the measurement to its next-hop neighbor. These activations can be periodic or single time. *Query-driven:* The query is disseminated from the base station, the node of interest resolves this query, and responds back to the base station. *Event-driven:* A sensor node sends a measurement towards the base station only if the given event occurs. Most routing protocols are belonging to multiple reporting models.
- **Communication Pattern:** The nodes in the network can communicate from the sink node to sensor nodes or from the sensor node to base station. It can be a reverse-muticast, unicast or anycast depending on the query and response.
- **Query based Support:** It is supported by all data centric protocols.
- **Energy Usage:** This is done relatively comparing the data aggregation protocols with the other protocols. This energy usage is estimated based on the network life time. It measures based on the time period when the first node dies after a consecutive number of rounds.
- **Application Type:** It is classified based on the application in which the data aggregation protocol is best appropriate.

5. Simulation

To evaluate the performance of some of the algorithms surveyed in this paper, extensive simulation experiments on Matlab was conducted. A random network topology built as shown in Figure 3 with an area of 50m x 50m dimension. Hundreds nodes are deployed randomly in the network. The sink node is located far away from the sensor nodes.

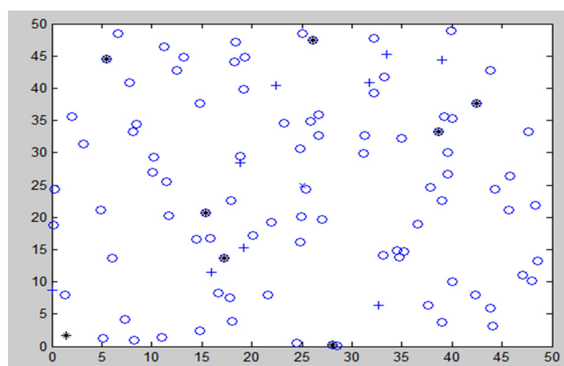

Figure 3. Screen shot of Random Topology building.

The performance parameters like lifetime of nodes[26] and average time taken to travel from source node to sink[27] are considered for the performance comparison of routing protocols. S. Lindsey et al.[28] discussed a first-order radio model, which is chosen for the analysis of the various routing protocol. The transmit and receive power requirements are calculated using the equations (1) and (2) using the assumptions on radio characteristics as shown in the Table 2.

Etx (k, d) = ETx-elec (k) + ETx-amp (k, d) (1)

Erx (k) = k (ERx-elec) (2)

Table 2. Radio characteristics

Initial node energy (Ei)	0.2 Joules
Transmitter Electronics (ETx-elec)	50 nJ/bit
Receiver Electronics (ERx-elec)	50 nJ/bit
Transmit Amplifier (ETx-amp)	100nJ/bit/m2
Number of bits for data transmission (k)	2000

The performance evaluation is done on SPIN, LEACH, PEGASIS, HEED, TEEN and SPAN routing protocols to perform data aggregation. The lifetime of a network is calculated by finding the number of rounds for which the first node dies in the network during simulation. The SPIN takes 591 rounds for first node failure. Similarly for LEACH, PEGASIS, HEED, TEEN and SPAN it takes 978, 1293, 1297, 1287 and 1407 respectively for its first node to fail. The node lifetime of the evaluated protocols are graphically plotted as shown in Figure 4.

The transmission time taken to send a data from the end node to the sink is another major factor which influences any routing protocol Figure 5 shows the average time taken to travel from source node to sink node. It is clear that the shortest time consumption has a strong binding to the network topology of the protocol. Thus, the performance analysis shows that the network topology has a high impact on the routing protocols to perform data aggregation.

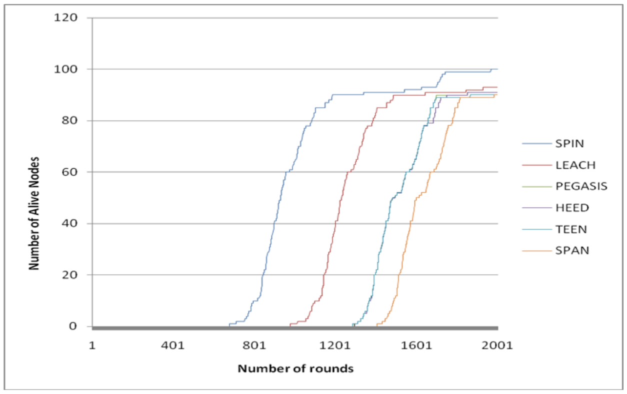

Figure 4. Node Lifetime.

Table 3. Summarization on tree, grid and hybrid based data aggregations

Aggregation based Routing Protocol	Network type Classification	Advantage	Limitation
DAA	Structure less	Event Based approach. In case of node failure, reconstruction of the structure is not required	Making routing decisions and performing aggregation is a challengeable task
EADAT	Tree	Broadcasting Approach is initiated by the sink node	To broadcast the help message, the procedure to determine the threshold power is not clear.
E-SPAN	Tree	Power Consumption is less in data transmission	Facilitates the sources within an event region to perform data aggregation
TAG	Tree	Query Based approach and reverse multicasting is supported	Establishment of the path is an overhead
TREEPSI	Tree	Power Consumption is less in data transmission	If the node fails the path has to go round-about way in the topology
GROUP	Grid	Distribute the energy load among sensor in the network and provide in-network processing	Frequently aggregation tree reconstructed CH's selected considers only the distance
ATCBG	Grid	Cluster head selection considers distance and energy	CH's selection and tree construction based on distance and energy
TCDGP	Cluster and Tree	Reduce energy Consumption	Node Recovery process is complicated
CCM	Chain and Cluster	Life time of the network is Improved	Overhead in choosing the cluster head
CLUDDA	Cluster and Diffusion	Inter cluster communication	Memory requirements are yet to be investigated
CBRP	Cluster & Tree	Centralized computation characteristics	Communication overhead due to many numbers of non-data messages exchanged between sensor nodes

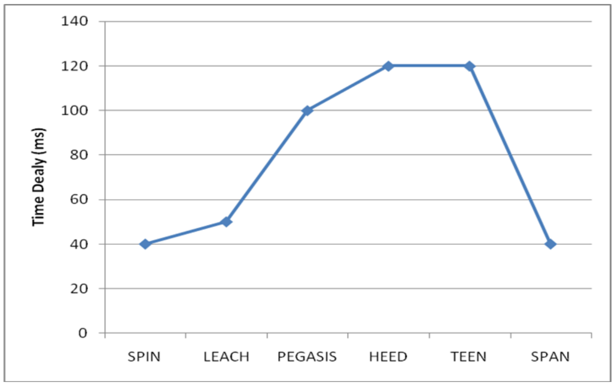

Figure 5. Transmission Delay.

6. Other Approaches

The various other approaches such tree based, grid base and some hybrid approaches are discussed and summarized as shown in Table 3. The tree-based approach of the hierarchical network, perform aggregation by constructing an aggregation tree. It is more suitable for performing in-network data aggregation[29]. For example, it could be a minimum spanning tree, where rooted at sink and source nodes are considered as leaves. Each and every node has a parent node to forward its data to the sink node. Flow of data starts from leaf nodes up to the sink and therein the aggregation done by parent nodes. The shortcoming of this tree based approach is the necessity of having a complete view of the network topology. *Energy-Aware Data Aggregation Tree (EADAT)*[29], *Energy-aware Spanning tree (E-SPAN)*[30], *Tiny Aggregation (TAG)*[31], *Tree-based Efficient Protocol for Sensor Information (TREEPSI)*[32] *data Aggregation Spanning Tree (AST)*[33] *and Power Efficient Routing with Limited Latency (PERLA)*[34] are some of the examples of tree based data aggregation. In grid based data aggregation the sensor nodes uses a fixed topology where nodes are placed in the form of a grid. Data aggregations are performed in local and global in two levels, which are performed by local and master aggregators respectively. In each and every region, local aggregation is performed at one cluster head and a subset of cluster heads known as master nodes are selected for global aggregation.

This type of aggregation is suitable for handling extremely low mobility nodes. Then the grid based protocols includes *Grid-clustering Routing Protocol for Wireless Sensor Networks - GROUP*[35] *and Aggregation Tree Construction Algorithm (ATCBG)*[36]. Then by combining the different structure based aggregation methodologies, some aggregation protocols are designed. The various aggregation protocols based on the hybrid mechanism are *Tree-Clustered Data Gathering Protocol (TCDGP)*[37], *Chain-Cluster based Mixed routing (CCM)*[38], *Clustered Diffusion with Dynamic Data Aggregation (CLUDDA)*[39], *Cluster Based Routing Protocol (CBRP)*[40] *and Link aware Data Aggregation Mechanism (LDAM)*[41].

7. Conclusion

The comprehensive survey on various routing protocols supporting data-aggregation algorithms in WSN is studied. The main focus of all the existing algorithm is on optimizes them based on the vital parameter. It includes energy conservation, improving the network lifetime and reducing the data latency. In this paper, the key features with its merits and challenges of the various existing data aggregation algorithm are discussed briefly. It is evident from the simulation results that infrastructure of the network strongly influences the performance of data aggregation protocol. Although, many routing protocol exists for data-aggregation techniques, the study proves that there is a scope for further research. Data aggregation approaches in the aspects of security, QoS is worth exploring.

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