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A survey of data aggregation and routing protocols for energy-efficient wireless sensor networks

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Abstract

The sensor nodes in wireless sensor networks (WSNs) typically have limited energy sources and are battery-operated. Reducing energy-usage, latency, and bandwidth is necessary to extend the network's lifetime. WSN is often deployed in dynamic environments where nodes in the network can join, leave, or fail at any instant. Dynamic topology changes can potentially disrupt established routes, necessitating more frequent route discovery and maintenance. Since a huge number of nodes are randomly deployed, a lot of redundant data packets are sent, which increases network traffic and creates delays. Robust and adaptable routing and aggregation techniques are necessary to meet these demands and adapt to shifting network conditions. The proposed survey paper offers a thorough analysis of the data aggregation mechanisms and energy-efficient routing algorithms applied to sensor networks. We have categorized the protocols depending on the network structure, data-gathering strategies, routing methodology, and node mobility. Based on the protocol performance parameters such as energy efficiency, network longevity, latency, routing overhead, packet delivery ratio, network throughput, and residual energy, we have provided a thorough classification and comparative overview of the key protocols. Moreover, we have determined the research gaps in the existing data aggregation techniques, and key areas which could point future researchers in the right direction.

Keywords: Wireless sensor network, Routing, Data aggregation, Delay, Packet delivery ratio, Network lifetime, Energy efficiency

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1. Introduction

Wireless Sensor Networks (WSNs) are becoming a key technology in many fields, including smart cities, industrial automation, healthcare, military, and environmental monitoring. WSNs identified a new type of multifunctional sensor that was made possible by developments in distributed signal processing, intelligent systems, and wireless communication technologies that can record a range of physical and environmental parameters. It is distinguished by its small size, limited battery life, low data processing capacity, and mobility, which allows it to form networks [1]. These constraints make it necessary to handle the routing process and data aggregation effectively to extend the lifetime of the network [2]. Figure 1 illustrates the fundamental architecture of data aggregation in WSN, comprising many sensor nodes, a cluster, an aggregator node or cluster head, and a base station or sink node. Data is sensed by the sensor nodes, which then send it to the aggregator node. All nodes' data is gathered by the aggregator node, which then transmits it to the base station.

In the wireless sensor network, the transmission routes that have been built may be disrupted by dynamic topology changes, which would require more frequent route discovery and maintenance. Routing protocols need to be robust and flexible to handle changing network conditions. Restricted bandwidth, limits wireless communication in WSNs, particularly in resource-constrained contexts. To reduce congestion and conserve bandwidth, routing protocols need to optimize data delivery. Prioritization, compression, and data aggregation are the strategies that can help lessen bandwidth restrictions [3].

Routing involves choosing the most efficient route from a source node to the destination node within a network. Routing in a WSN differs from traditional networks in various aspects, including the possibility of a sensor node failure, which renders wireless links unstable, and the need for routing protocols to accommodate the energy needs of the sensor nodes [4]. The most efficient path for data transmission is chosen depending on several factors, including bandwidth, latency, hop count, and energy. Routing methods minimize network congestion by selecting effective paths, which enhances overall network performance and data delivery rates. Choosing a correct routing protocol that guarantees fast, safe, and effective data transmission in both small-scale sensor networks and large- scale networks is a challenge. WSN routing protocols are categorized based on the architecture of the network into three groups Flat-based routing, Hierarchical-based routing, and Location-based routing [5].

As per another study [6], [7], the four primary categories of routing protocols are data-centric, hierarchical, location-based, and multipath-based routing protocols. The network topology changes constantly due to node failure, the addition of new nodes, mobile nodes, or changes in the network environment. Adhoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Optimised Link State Routing (OLSR) [5] are utilized to address the problems caused by the dynamic nature of such networks, where nodes are mobile and the network topology is constantly changing. Numerous monitoring applications, including those in the armed forces, agriculture, healthcare, transportation, and industry, use these protocols to keep an eye on the physical surroundings. Both the AODV and DSR protocols exhibit the same on-demand behaviour, according to theoretical study and simulation results, but differ in terms of performance due to their differing protocol mechanics [5]. Furthermore, they have greater end-to-end latency. To mitigate the latency, the Optimised Link State Routing (OLSR) protocol can be used. The outcomes of OLSR could prove beneficial in the deployment of wireless sensor networks for various control and monitoring applications.

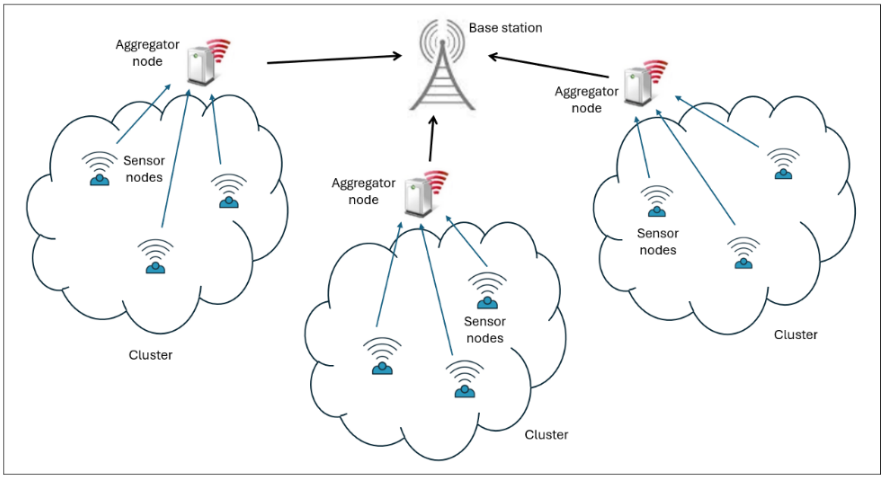

Figure 1. Data aggregation in WSN

There are several difficulties, including creating a dependable, dynamic topological structure, allowing for high node mobility, low node density, energy constraints, and stable routing in flying ad hoc networks (FANETs). Thus, for data to be sent between drones, a routing algorithm's design is crucial. In flying ad hoc networks, an energy-aware routing strategy based on a virtual relay tunnel (EARVRT) [8] is suggested in this research. To reduce network overhead and manage relay nodes throughout the route-finding process, EARVRT incorporates a virtual relay tunnel (VRT).

In the novel method [9], multi-hop routing algorithms and clustering operate simultaneously to reduce control packets. Clusters are created so that cluster leaders have the highest level of competency in forwarding tasks of intra-cluster and inter-cluster transmission trees based on non-uniform energy consumption among nodes. The three primary adjustment factors for cluster head election are energy consumption, adjustment degree, and the precise distance that each data point travels to reach the base station.

Gathering data from sensor nodes, eliminating the redundant data, and transmitting it to the sink node is considered data aggregation [10], [11], [12]. The sensor data arriving from the sensor nodes is aggregated using a variety of techniques, including Tiny AGgregation (TAG) [13], centralized approach, and low-energy adaptive clustering hierarchy (LEACH) [14]. The data-gathering mechanism combines the sensed data by using aggregation functions like Maximum, Average, Sum, Mean, Median, and Difference [10] or other functions like Match and Correlation-coefficient [11]. Combined data forms a single data packet which is sent to the intermediate node by taking advantage of temporal and spatial redundancy. A decrease in data redundancy will extend the network's lifespan and lower the latency [12]. Data aggregation effectively transmits all of the network's information to the sink node [15], [16], [17]. Multi-hop communication, data aggregation, and clustering are the three main strategies to lower network energy usage. [18] discusses several network structure-based data aggregation strategies, including flat and hierarchical networks. In hierarchical networks, data aggregation is further categorized into cluster-based aggregation and chain-based aggregation [19], [20].

To enable effective routing and communication in large scale networks without taxing the network's capacity, scalable routing protocols are required. Scalability in WSNs can be attained through the use of distributed and hierarchical routing techniques [21]. However, load balancing across all nodes prevents nodes from dying too soon. To provide load balancing, an ideal scalable Optimal Clustering in Circular Networks called OCCN is presented in [22].

Contributions to the work:

We have categorized the current routing and aggregation protocols according to the network structure, routing strategy, aggregation approach, path establishment, and node mobility. We have also reviewed the classified protocols and determined their shortcomings. Further, we have illustrated the working mechanism of data collection models based on the data gathering method and the need of the application, and presented the challenges in the data communication models. We have identified the research gaps in the current data aggregation mechanisms, which may provide direction in the key areas for future research.

The paper is organized as follows. Section 2 covers the survey including classification and comparison of routing and data aggregation algorithms. Section 3 provides the challenges in data collection models in WSN. Section 4 discusses the future research directions in key areas. Section 5 presents the conclusion.

2. Data Aggregation and Routing Mechanisms

Data aggregation is the process of gathering and combining data from multiple sensor nodes to produce a summarized or composite dataset. It is frequently easier to handle and analyze this aggregated data, which facilitates analysis, interpretation, and decision-making. Effective data aggregation techniques can minimize the network traffic, increase the network lifetime, and achieve load balancing. In this section, we have classified the key data aggregation mechanisms based on the network structure, communication model, routing type, and node mobility as shown in Figure 2. We have also provided a comparative overview in terms of network energy consumption, delay, bandwidth, residual energy, network lifetime, and communication overhead.

2.1. Network structure

This section examines several aggregation techniques specifically targeted towards WSN network design. The data aggregation and routing mechanism of WSN is dependable on its network structure [18]. The data transmission in network structure-based aggregation is bifurcated into flat, hierarchical, and location-based routing.

2.1.1. Flat routing

In this technique, every node has an equal role, and routing choices are decided upon cooperatively. Flooding algorithms fall under this group. With its straightforward methodology, every node broadcasts data to its neighbours. Examples of flat-based routing protocols include SPIN (Sensor Protocols for Information via Negotiation directed Diffusion) [18] and AODVI (Ad hoc On-demand Distance Vector Routing Protocol based on Dynamic Forwarding Probability) [23].

In flat-based routing, each node transmits the data to the sink node using multi-path which causes flooding. The

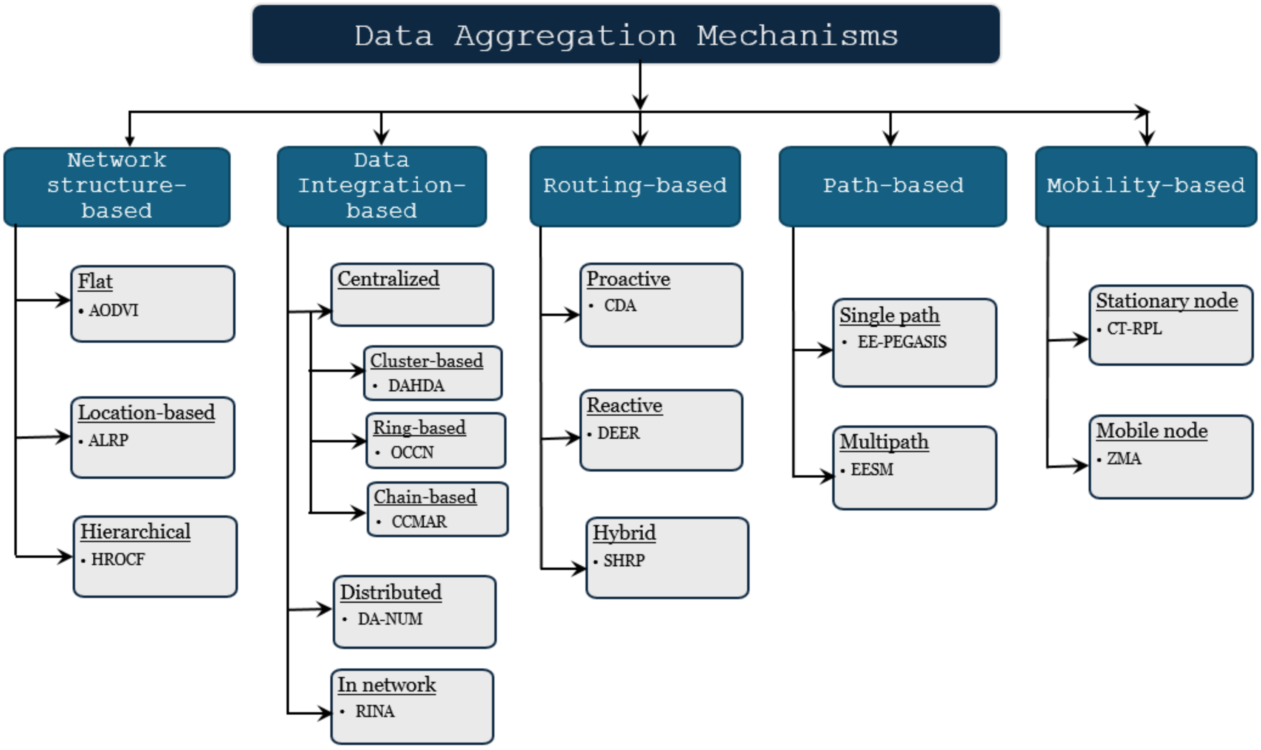

Figure 2. Data Aggregation Mechanisms

flooding of data leads to redundancy so, a large amount of the energy is wasted to transmit redundant data to the sink node. Due to multipath transmissions, there is also a delay in receiving the data at the sink node. Further, if the sink node fails, the network will go down leading to an increase in routing overhead.

Ad hoc On-Demand Distance Vector Routing Protocol based on Dynamic Forwarding Probability (AODVI):

The original AODV uses a simple flooding approach to discover the route, in which a source node broadcasts to every other node in the network. Conversely, this tactic uses more network traffic and draws more power from the batteries. However, the AODVI [23] protocol effectively addresses the performance issues caused by AODV routing protocols by switching to a probabilistic message-transmitting scheme that uses probability to determine the number of nodes that will transmit the messages. In AODVI, the intermediate nodes rebroadcast the RREQ packets only to the specific nodes based on the message forwarding probability at the intermediate node. The dynamic forwarding probability is a function of the control factor, minimum number of neighbours, and a random number.

Limitations-

There should be a sufficient delay in rebroadcasting RREQ packets otherwise collisions may happen which would prevent the packet from reaching its destination and affect the path-finding process. The failure of nodes causes logy so new routes need to be established, often resulting in depletion of network energy and increase in routing overhead.

2.1.2. Location-based

This method uses the geographic information of nodes to determine the physical location of nodes on which it makes routing decisions. Modified Geographical Energy-Aware Routing Protocol [25], and ALRP [26] are based on Location-based routing.

Adaptive-Location-based Routing Protocol (ALRP):

The ALRP protocol [26] uses the sensor nodes’ three-dimensional geographic location data to determine the best route. It is assumed that every node knows its position through GPS or other underwater positioning systems and may also know the positions of the nodes that are next to it. The protocol constantly modifies its routing approach in response to node mobility, node density, current network conditions as well as environmental factors affecting communication quality. The distance to the destination, the nodes’ energy levels, and the communication link’s quality are some of the parameters that the protocol takes into consideration while determining paths. The protocol may react to changes in environmental factors and network structure by modifying the route selection criteria. In its initial stage, the protocol might employ a greedy forwarding strategy in which every node sends data to the node next to it in 3D space that is the closest to the destination. By using this technique, energy is saved and fewer hops are required. The protocol may employ a recovery technique, like going back to a prior node or choosing a different path, to guarantee data delivery if greedy forwarding fails (for example, when a node lacks a neighbour closer to the target).

Limitations-

For routing decisions, the protocol mostly depends on precise location information. Due to the difficulties with underwater positioning systems (e.g., GPS signals cannot penetrate water, requiring alternate approaches such as sound localization), it can be challenging to collect exact location information in underwater situations. Erroneous or delayed location information may result in poor routing choices, raising the risk of communication malfunctions or excessive energy consumption. The protocol's adaptive feature, which modifies routing choices in response to a range of dynamic variables like node density, mobility, and energy levels, complicates its implementation and increases the computational burden on sensor nodes. The protocol makes routing decisions using heuristics such as greedy forwarding, which may not always produce the best path, particularly in irregular 3D topologies.

2.1.3. Hierarchical routing

This method organizes nodes into clusters with cluster heads(CHs) responsible for routing and aggregating data to the base station. Examples are LEACH [27], FBECS [28] and HROCF protocols [29]. The CH aggregates the data from cluster member nodes. Forming a cluster and selecting of cluster head adds complexity to the network protocol. There is a single-point failure if CH dies and re-election of CH increases communication overhead.

Hierarchical Routing with Optimal Clustering using a Fuzzy System (HROCF):

In HROCF [20], the network is divided into various regions, and the HROCF protocol is implemented in three stages. The first stage involves the formation of clusters, the second stage refers to establishing a hierarchical routing path from lower regions to upper regions and the third stage indicates data transmission. Each round has two phases set-up phase and steady-state phase. The cluster leader (CL) is selected during the set-up phase using the fuzzy inputs: position, communication cost, and residual energy. In the steady-state phase, hierarchical routing transfers data from the lower region to the upper regions and finally to the base station.

Limitations-

If the CL fails, then there should be an alternate mechanism to replace the failed CL or election of CL. Additionally, when CLs in the uppermost region die there may be a cascading effect due to which packets would not reach the base station. So providing node scheduling for the CL to remain active can reduce this problem. Election of CL is based on its position with respect to other nodes so GPS is utilized by the nodes, making the system more costly.

2.2. Data Integration approach

The aggregation mechanism is categorized into three types: centralized, distributed, and in-network aggregation based on how the nodes collect their data at various locations in the sensor network [30].

2.2.1. Centralized aggregation

A central node maintains a record of every other node and gathers data about every node in the network as part of the centralized algorithm [30]. Additionally, it keeps the same information in its database. Any node must ask the central node for permission to interact with any other node. Centralized algorithms are further distributed as cluster-based and tree-based. In cluster-based algorithms, the aggregator nodes are cluster heads, whereas in tree-based algorithms, the aggregator nodes are parent nodes. Some of the existing centralized algorithms are the OCCN (Optimal Clustering in Circular Networks) algorithm [22], CCMAR (Cluster-chain Mobile Agent Routing) algorithm [31], EECS (Energy Efficient Clustering Scheme) [15], DAHDA (Dynamic Adaptive Hierarchical Data Aggregation) algorithm [32] and LEACH [27]. Centralized aggregation can be simple cluster-based, ring or layer-based, and chain-based.

Dynamic Adaptive Hierarchical Data Aggregation (DAHDA) : – Cluster-based

The DAHDA [32] algorithm is distributed in four steps. In the first phase, the nodes transmit their position coordinates to the sink node. Base stations divide the whole network into four quadrants during the second phase to offer connectivity and coverage. The third stage describes the cluster formation process using a Meta-Heuristic computational-density-based clustering mechanism (MHC-DC) [33], [34]. MHC algorithm is used for forming the cluster based on cluster radius and minimum number of nodes inside the cluster. The weight assignment phase, which occurs in the fourth stage, assigns weights to each node based on the density of their neighbour nodes. The data-sending nodes are those with lower weights and they must transfer the data to the appropriate cluster head. When there are fewer nodes in a cluster than necessary, the cluster formation process is repeated.

Limitations-

A backup CH or relay node should be in place in case the CH fails in a given round. Otherwise, the CH may fail to identify an event in the monitored field. Mostly the sensor nodes use GPS modules to obtain the location of nodes. It is not always possible to add a GPS module to the sensor node due to the following reasons. First, the GPS module requires a line of sight for the GPS satellites. If this is deployed in a deep forest or, in certain situations, on a mountain, it might not be feasible. Second, the network lifetime would be shortened due to the GPS module's power consumption reducing the sensor node's battery life. Third, the GPS module might be larger than the node. This can lead to deployment issues where node size is critical.

Optimal Clustering in Circular Networks (OCCN) : – Ring or Circular-based

An ideal scalable clustering technique called OCCN is presented in [22], which uses optimal-sized clusters and optimal multi-hop packet relaying to guarantee fair traffic forwarding. In the OCCN algorithm, the network is first divided into rings surrounding the sink node in a circle. The distance between the two rings represents the ideal distance between the two nodes. The sink node forms a fixed number of clusters in each ring. Every node is given a certain amount of time to serve as the cluster head, to reduce the energy and time used during the process. Thus, all nodes periodically switch roles because the energy consumption of CH nodes is significantly higher than non-CH nodes. Each node randomly selects a time slot from a window of available times. In the OCCN algorithm, this step is referred to as the reservation phase. Then, within its communication range, each node transmits its ID and the details of the reserved time slot. Each node that receives these messages will measure its distance from other nodes. Every node transmits its location data to the sink, assuming it has a global positioning system (GPS). A node is chosen as the CH, whichever is closest, based on the received reservation messages. To provide load balancing among the clusters, the cluster head must choose the precise number of cluster members for each cluster. OCCN is a significant improvement over LEACH [27], HEED [35], and the method suggested in [36].
Limitations-

There is a considerable chance of packet collision during the reservation-based set-up phase when each node tries to reserve its timeslot to become the cluster head. The use of GPS may consume more battery power from the resource-constraint nodes which can reduce the lifetime of sensor node.

Cluster-Chain Mobile Agent Routing (CCMAR) : – Chain-based

The CCMAR [31] algorithm is developed to minimize energy usage and delay while extending the network's lifespan. Three steps can be used to categorize the CCMAR algorithm. Cluster heads are selected from all sensor nodes during the first step, then a collection of nodes forming the cluster in the second step, and finally cluster is assigned to each cluster head(CH) in the third step. The concept of clustering aids in keeping nodes' remaining energy for extended periods. PEGASIS [37] is utilized in the second step to create the chain connecting sensor nodes for data aggregation. Mobile Agents (MA) are utilized in the third step to help collect data from the CH and minimize transmission latency. MA also assists in obtaining data from the CH to minimize the energy usage of the cluster head. LEACH [27], PEGASIS [37], and EECP (Energy efficient cluster-chain based protocol) [38] are used to compare the outcomes of CCMAR. It has been noted that the CCMAR outperforms current algorithms in terms of network lifespan, transmission latency, and energy usage.
Limitations-

Using CCMAR, the data from the most distant node is sent to the next consecutive node and finally to the CH creating a chain. There is a chance that a significant amount of redundant data will be accumulated at CH when each node receives data from the preceding node, adds its data to the received data, and forwards it to the next node. In the process, nodes will expend more energy to carry redundant data to the CH. Furthermore, redundant data must be removed at CH before being collected by a mobile agent (MA), otherwise, there may be a significant delay in the redundant data being transmitted from a single MA to the sink node.

2.2.2. Distributed aggregation

Any node can communicate with any other node without a centralized request. In this case, each node contributes equally to the packet routing process. Each sensing node can be an aggregator node. One of the distributed algorithms is DAS (Distributed Data Aggregation Scheduling) [39].

Distributed algorithm based on Network Utility Maximization (DA-NUM) :

The Distributed algorithm based on Network Utility Maximization (DA-NUM) [40] finds the optimal routing path by considering end-to-end delay and energy consumption. The Network Utility Maximization (NUM) framework is used to maximize the average utility of the network, under the constraints on link rates, reliability, information rates, and average power transmitted. In this algorithm, three types of nodes, i.e. source nodes, sink node, and forwarding nodes are considered in the network. The network operates in a low duty- cycle mode to conserve network energy. It optimizes the problem of minimizing the average transmission delay in the network by applying the Lagrangian function. Each node is initialized with a Lagrange Multiplier in each iteration. By using the edge weight of neighbour nodes, each node finds an optimal path by using the Bellman-Ford algorithm after certain iterations. Then the node updates the Lagrange multiplier and broadcasts it to neighbour nodes. This process is repeated until it reaches the threshold value. As the algorithm follows low duty-cycle nodes, the total flow of incoming traffic load at each node is reduced, minimizing the collisions in the network.
Limitations-

The propagation delay and data transmission delay in the wireless channel need to be considered. The computational complexity of the algorithm may be increased due to the updating of Lagrange Multipliers by each node for every iteration. When dealing with dense networks, where the number of edges is nearly equal to the square of a number of vertices or nodes, the Bellman-Ford approach may be especially inefficient. For large networks, the algorithm becomes slow for non-negative weights and increases the time complexity.

2.2.3. In-Network processing

In this technique, progressive data aggregation occurs as it moves across the network. To reduce energy depletion, the sensed values of the nodes are collected at mid-nodes. Reducing the rate of power consumption at each node also lengthens the lifespan of the network. An example is the PPSDA (Privacy-Preserving Secure In-network Data Aggregation) [41], SDAP (Secure data aggregation protocol) [42] and SEEDA (Secure end-to-end data aggregation protocol) [43], RINA (Routing algorithm for In-network aggregation) [44]. Aggregation applications often process vast amounts of intermediate data from multiple aggregator nodes to produce final results. This generates significant traffic due to the transfer of intermediate results [45].

Routing algorithm for In-network aggregation (RINA) :

The RINA protocol [44] uses Q-learning, a reinforcement learning technique, for routing. It builds a routing tree using minimal data, including residual energy, node distances, and link strength. protocol. It also identifies aggregation points within the routing structure to optimize overlapping routes, thereby enhancing the aggregation ratio. There are two phases in the protocol, first is finding the routes and second is finding the aggregation points. RINA protocol solves the "void problem" by dynamically adjusting routes and maximizing overlapping data paths to improve aggregation efficiency.

Limitations-

The protocol assumes homogeneous sensor nodes, which may limit performance in diverse real-world scenarios. While RINA addresses routing voids, proximity to void regions remains a potential limitation for data forwarding.

2.3. Routing strategy

Routing strategy-based protocols are bifurcated into proactive, reactive, and hybrid routing protocols according to how they handle routes. Proactive protocols update more frequently than reactive protocols, resulting in higher overhead than reactive protocols, which do route discovery on-demand.

2.3.1. Proactive routing protocols

Table-driven protocols, also known as proactive routing protocols [5], compute all routes before they are used and distribute periodic routing information to accurately maintain routing tables of all sensor nodes in the network. Network structures that are flat or hierarchical can benefit from the usage of proactive routing techniques. An example of proactive routing protocol is CDA [46] which is discussed in the next section. Proactive routing protocols are limited to static WSN environments.

Collaborative Distributed Antenna routing protocol (CDA) :

In the CDA protocol [46], using the Degree Constrained Tree (DCT), the total number of nodes is uniformly distributed and divided into various hierarchical levels where the BS is at the root level. An optimum number of levels and the optimum number of children (referred to as the node degree) are found to minimize the total energy consumed in the tree. When the network starts up, a node is selected randomly to serve as the Region of Interest's (ROI's) Virtual Base Station (VBS) by acting as the tree's root. After that, all of the tree's nodes' data is aggregated to reach the selected root VBS, and this process is repeated several times until the root VBS's energy level reaches a certain threshold. Apart from data collection as the root of a tree, the VBS also distributes the aggregated data packet (PTB) with control information for synchronization on a chosen set of nodes known as Distributed Antenna Elements (DAEs). VBS selects the DAEs within the threshold distance, and these DAEs transmit the PTBs to the BS. In this way, VBS works together with the DAEs to form the distributed antenna system in ROI to BS transmission.

Limitations-

The additional synchronization control information and node information in the packet leads to an increase in the size of multicasted PTB data packets routed through the tree as compared to the size of data packets transmitted directly to the BS which leads to an increase in transmission overhead, and energy consumption. The protocol model can be applied to static WSNs only and can be aimed at dynamic environments.

2.3.2. Reactive routing protocols

Reactive routing protocols [4] use the route query before route establishment to create a path between a source node and the destination based on demand. They do not keep track of all the nodes in a network. These strategies differ in that they minimize communication overhead brought on by network congestion, and they re-establish and re-compute the path after a node dies. Examples of reactive routing protocols are AODVI [23], DSR, and CLUBAA [47], and DEER [48].

Dynamic Energy Efficient Routing (DEER) :

In DEER [48], a reactive approach is used which works in two phases. In the first path-finding phase, the best path is selected according to the residual energy of individual nodes. During the second relaxation phase, the reactive strategy aids in removing the malfunctioning nodes from the link. After a certain waiting period, new nodes are employed for the link if any intermediary relay fails.

Limitations-

The algorithm uses the greedy approach to find the path from the source node to the sink node. According to the greedy approach, the packet travels from the source node to the node with high residual energy which may reside opposite to that of the destination or sink node. This offers excess delay in data transmission to the sink node. Additionally, the transmission cost will be increased and due to more number of hops reaching the destination, network energy consumption will also increase.

2.3.3. Hybrid routing protocols

For huge networks, hybrid routing strategies [4] combines proactive and reactive routing techniques. Utilizing the clustering technique, the entire network is split into numerous clusters; each kept up to date dynamically whenever a node joins or leaves. When routing is required between clusters, this protocol employs a reactive technique; otherwise, a proactive technique is used. Examples of hybrid routing protocols are SALMA (State-Aware Link Maintenance Approach) protocol [49] and SHRP [50].

Secure hybrid routing protocol (SHRP) :

A secure hybrid routing protocol [50] is developed based on Multipath Optimized Link State Routing (OLSR), Destination Sequenced Distance Vector (DSDV), Topology Change Aware-based routing (TARCS) and Ad hoc On-Demand Multipath Distance Vector (AOMDV). It is discussed in several steps mentioned below.

Initial set-up - Initially when the network is set up the source node broadcasts hello packets through multipoint relays and thus identifies its neighbour nodes using the OLSR protocol.

Selection phase of neighbours - The protocol verifies the number of sequential requests and responses and updates the link-state topology table after identifying one and two-hop neighbour sets based on a minimum number of requests and responses.

Secure monitoring and multiple channels selection - The nodes are designated for the purpose of continually monitoring the data transmission across multiple channels while they are in motion. The protocol chooses the forwarding nodes with their neighbours on various channels and create Concealed Monitor Sets (CMS).

On-demand route maintenance and secure transmission - After completion of CMS formation, the AOMDV is further responsible for monitoring the routing path.

Aggregating and monitoring report updates - The protocol chooses the sensor node to act as a monitor, performing a pattern-matching function to verify the authenticity, the node’s behaviour, and the transmitting nodes’ traffic patterns. The security level of cryptographic applications is examined using the key encryption and decryption blocks.

Limitations-

The request and response messages include node-id, sequence number, hop count, packet number, neighbour-node identity, and timer which increases the packet size and poses a heavy transmission overhead for a large network. If the selected monitoring nodes exceeds or equals twice the number of nodes per number of channels then two monitor nodes should be maintained for each sensor node. That may result in fewer nodes for sensing and forwarding the data compared to the monitoring nodes and increasing the computational complexity. If the transmission link breaks then alternate routing paths are difficult to identify without delay as the nodes are in motion. The sensor nodes’ limited processing power may be strained by the computational overhead due to encryption and authentication.

2.4. Path establishment

Path establishment refers to the procedures and formulas used to establish and preserve the paths or routes, the data packets take from source nodes to the base station. Single path and multipath routing are the categories with unique techniques and features.

2.4.1. Single-path routing

It uses a single optimal path for data transmission based on shortest path criteria. Examples are Advanced Fixed Path Mobile Sink Energy Efficient PEGASIS-based Protocol and CCMAR (Cluster-Chain Mobile Agent Routing) protocol [31].

Advanced Fixed Path Mobile Sink Energy-Efficient PEGASIS-based Protocol :

The suggested approach in [51] focuses on the movement of the base station as stated by a multiple-chain system to achieve tiny chains and lower the burden on the only leader node, which directly impacts the lifetime and energy conservation of the network. Extended single chains are likewise accountable for more notable delays in the data transmission process. This fact is inappropriate for operations prone to or intolerant of delays. This research focuses on adjusting the moving base station’s trajectory to confine it to several locations. The motion of the base station (BS) is divided into three segments. First, each of the four clusters’ fixed times for the base station are determined. Depending on these time slots, the base station embarks on its journey and makes stops at the specified locations. The base station then determines how long each round will last. Based on this input of time, BS determines the total duration of stay for each of the four fixed sites.

Limitations-

As the protocol depends on a single fixed path, it cannot adjust to fluctuating traffic loads, i.e. when the network environment changes. The protocol may not work well for a large-size network as more chains need to be created which may increase routing overhead.

2.4.2. Multipath routing

It establishes multiple paths from the source nodes to the base station to increase reliability and load balancing. Energy Efficient Secure Multipath (EESM) routing protocol [52] is an example of a multipath routing protocol.

Energy Efficient Secure Multipath (EESM) Routing protocol :

This study [52] suggests a safe multipath routing technique that is energy-efficient and creates numerous secure routes for each node to send the data to the base station (BS). Using the node-level and network-level information, such as location, quality of the communication link, and residual energy, safe and energy-efficient multiple disjoint pathways are built to ward against security threats. It guarantees security during each of the three stages of the network, i.e. maintenance, data transfer, and route building. It employs a robust cryptosystem that encrypts text data using a pseudorandom bit sequence generated by a chaotic map. Each sensor node has a unique elliptic curve point, one of the secret key parameters for encryption and decryption.

Limitations-

More energy may be consumed while transmitting the same data through multiple paths from the source node to the sink node. Additionally, the communication overhead may be high due to numerous routing paths.

2.5. Mobility

The protocols for data aggregation can be designed by considering either stationary or mobile nodes. In mobile-based routing, any of the following three possibilities must be taken into account by data aggregation systems that handle mobility by making both or either the sink or the sensor node mobile.

2.5.1. Stationary node-based routing

It is applicable for stationary nodes and optimizes routing for static networks. An example is LEACH, PEGASIS, and CT-RPL [53].

Cluster Tree-based Routing Protocol (CT-RPL) :

Cluster creation, cluster head selection, and route establishment are the three processes that make up the CT-RPL [53]. The network comprises of destination-oriented directed acyclic graph (DODAG) in which DODAG root is deployed on the top of the network. In the cluster creation process, the Euclidean distance between the nodes is computed to build the cluster. A game theoretic method is employed to select the CH. In this method, the node in each cluster that has the highest payoff value for that specific round serves as a CH node. The payoff value represents a reward or penalty of a particular node action in the game and it is calculated based on the reward value, penalty value, residual energy, and energy depletion ratio of the particular node. In the route establishment process, the expected transmission count (ETX), queue utilization (QU), and residual energy ratio (RER) are used to construct the route.

Limitations-

Resource constraint nodes may have limited buffer sizes so less number of packets will be accommodated in the queue and the number of data transmissions may decrease. Path loss causes the wireless signal's intensity to diminish with distance, making transmissions weaker at longer distances. Hence the link quality degrades so the expected transmission count would be minimal. GPS may be used to get the location of nodes and compute the Euclidean distance between them. Since the nodes have limited resources, adding GPS to them would be more energy-intensive and costly.

2.5.2. Mobile node-based routing

It is designed to handle the mobility of nodes within the network. This mechanism adjusts to the mobility of nodes by reorganizing clusters dynamically. Examples of the protocols are ZMA (Zone-based Mobile agent Aggregation) [54], and DRE (Degree Restricted Tree) [55].

Zone-based Mobile Agent Aggregation (ZMA) :

The Zone-based Mobile Agent (ZMA) [54] approach is a routing protocol that moves multiple mobile agents (MAs) to aggregate the data in the network. This protocol routes the MAs over a zoned network to collect and aggregate sensory data. The network is divided into several concentric zones around the sink. To initiate the Mobile Agent (MA) migration, a group of nodes in each zone are designated as Zone Mobile Agent Coordinators. During data aggregation routing, Zone Mobile Agent Coordinators (ZMACs) are responsible for initiating the mobile agent's mobility in each zone. In ZMA, ZMAC is elected using three steps. In step 1, the Vicinity-discovery phase, every node locates its vicinity area by attempting to connect to any neighbour within the same zone that possesses the same kind of data. In step II, to determine which nodes are most likely to become ZMACs in each zone, ZMA uses a weighting function based on node connectivity degree, residual energy, and proximity to the event sources. In step III, the MAs move from ZMACs to the sink using the bottom-up approach. The sink adjusts its radio communication range to send a message to a particular part of the network. Using this approach, only the ZMACs stay on duty to receive data requests and other ones go to sleep to conserve energy.

Limitations-

Nodes broadcast control messages throughout the zones in the vicinity-discovery phase in addition to the zone-forming phase, which may cause excessive routing overhead. In wakeup time ZMAC remains on duty for longer durations and may exhaust their energy and need to re-elect ZMAC which may consume more energy and increase in control overhead.

The contribution and brief limitations of data aggregation and routing protocols are mentioned in Table I. We have compared the data aggregation algorithms based on their performance parameters, and a tabular representation is provided in Table II. In table II, '√' means the evaluation/performance parameter is considered and 'x' means that the parameter is not considered for the comparison. Table II shows the relative performance measurement of the compared protocols. It shows the quantitative analysis based on the data presented in the respective papers. The detailed limitations of each data aggregation technique is presented in Table III.

The challenges and methods of data collection models, which are based on how the data is aggregated and the needs of the applications, are covered in the following section.

3. Challenges in Data Collection Models

Data collection is necessary to obtain real-time information on variables like temperature, humidity, soil moisture, and

Table 1. Classification of Data Aggregation and Routing protocols

Aggregation Mechanism	**Aggregation Types**	**Aggregation Protocol**	**Brief Description**	**Contributions**	**Limitations**
Network Structure	Flat-based routing	AODVI, [23]	Information of neighbour nodes and probabilistic method is used to find the route	Source node rebroadcast the route reply messages only through uncommon neighbour nodes, thus reducing redundancy of re-broadcasting route-request packets	i) Route request packets are randomly controlled which may reduce the network efficiency ii) Route instability due to change in network topology, so new routes need to be established which may cause delay in data transmission
	Location-based routing	ALRP [26]	ALRP designs the forwarding area to determine whether the nodes take part in forwarding, it calculates forwarding probability, and forwarding delay.	Adaptively calculates the data forwarding probability based on the distance between the current nodes and the plane, allowing the nodes closer to the destination node to have a higher forwarding probability and reducing redundant forwarding	i) Highly computational to continuously adjust forwarding probabilities in real-time, which could slow down the routing process. ii) Any location estimation inaccuracies may result in poor forwarding probability adjustments.
	Hierarchical routing	HROCF, [29]	Cluster leaders(CL) are elected through fuzzy inputs such as location of the nodes, balance energy, and cost. Then hierarchical routing is used to communicate data to SN from lower region via upper region through CLs.	Based on the location of the nodes, balance energy, and cost, the HROCF forms the cluster including nodes inside the cluster including cluster leader with an appropriate network traffic balance	Hierarchical fuzzy based routing without redundancy elimination may increase delayed packet transfer
Data Integration Approach	Centralized aggregation	DAHDA, [32]	Uses concept of weighted sensors, to decide selection of CH's subject to remaining energy and node quantity	Includes adaptivity feature to overcome rapid bursts in the data for improved accuracy	i) GPS position of the sensors are required that may not be cost effective ii) Applicable to network with small node density
	Distributed aggregation	DA-NUM, [40]	Apply greedy algorithm to form a chain in the sub-network	Leader node is selected in each sub-network such that it provides a short distance from all other nodes. Leader nodes fuse data from other nodes and transmit to sink node resulting in low transmission delay and high scalability	In dynamic topology, it is difficult to locate nodes to form a chain, leading to additional routing overhead
	In-Network processing	RINA [44]	Uses Q-learning, a reinforcement learning technique for routing	It reduces the requirement for global information by choosing the path adaptively based on neighbors' local information. In dynamic scenarios, it also carries out data aggregation and packet routing effectively.	Optimal performance requires careful tuning of energy thresholds, which can be situational.
Routing Strategy	Proactive routing	CDA, [46]	Degree Constrained Tree (DCT) is implied in CDA routing protocol with	In DCT, to reduce energy consumption, the desired node degree is determined as three	Protocol is applicable only if nodes are uniformly distributed over the Region of interest

Aggregation Mechanism	Aggregation Types	Aggregation Protocol	Brief Description	Contributions	Limitations
			desirable node degree and is meant to monitor periodic data		
	Reactive routing	DEER, [48]	Uses the greedy approach to find the best path from the source node to the sink node based on the node residual energy	Malfunctioning nodes are removed from the link. Waiting time is incorporated, to add new nodes in the link if any intermediate relay fails	Data packets may travel to the node residing in the opposite direction to that of the sink node which may consume more energy, excess delay, and maybe cost-inefficient.
	Hybrid Routing	Secure hybrid routing protocol, [50]	Based on Multipath OLSR, DSDV, TARCS, and AOMDV protocol to obtain secure routing path	Nodes identify its neighbour nodes using the OLSR protocol. Updates the link-state topology table after identifying one and two-hop neighbour sets. Provides on-demand route maintenance and secure transmission	Handling frequent topology changes and keeping links in their current state can be difficult in extremely dynamic environments
Path Establishment	Single-Path routing	Mobile sink EE PEGASIS-based Protocol,[51]	Employs a multiple-chain approach to focus on stated mobility of sink node in order to form chains of small size and lower the burden on the only leader node	The total data transfer is more advantageous with many leaders in the chains compared to one leader in a chain	Protocol may not work well for large size network as more chains need to be created which may increase routing overhead and energy consumption
	Multipath routing	EESM, [52]	Builds safe and energy-efficient numerous discontinuous pathways based on information such as position of node, quality of link, and residual energy to avert security attacks	Uses a unified implementation framework called CGEA, which is a robust cryptosystem. Each SN in this system has a unique elliptic curve point, which is the secret key parameter to encrypt and decrypt data	i) More energy is consumed while transmitting same data through multiple paths to sink node ii) Communication overhead may be high iii) Nodes procured with GPS maybe costly
Mobility	Stationary node-based routing	CT-RPL, [53]	Euclidean distance between the nodes is computed to build the cluster. A node in each cluster with the highest pay-off value for that specific round serves as a CH node	Pay-off value is used to determine the route based on the reward value, penalty value, residual energy, and energy depletion ratio of the particular node so bottleneck problem at sink node is fixed	i) Limited buffer size result in small queue size so number of data transmissions may decrease ii) Path loss makes transmissions weaker at longer distances. Hence link quality degrades so the expected transmission count is minimized
	Mobile node-based routing	ZMA, [54]	Mobile agents(MA) migrates from bottom to top, beginning their travels to sink from event region's centre to decrease cost and duration of the MA itinerary	i) Dynamically determines best routes for the MA's to travel over the network to aggregate data ii) Zone Time is incorporated which is the amount of time after which nodes broadcast a zone enquiry message	Nodes broadcast control messages throughout the vicinity-discovery phase in addition to zone-forming phase, which may increase routing overhead

Table 2. Comparison of data aggregation algorithms based on performance metrics

Note: ‘√**’** indicates, performance parameter is considered; ‘x ‘indicates, not considered; DNA* - Data Not Available; (+) Higher by; (-) Lower by;

Aggregation mechanism	**Aggregation Protocol**	**Compared protocol**	**Routing overhead**	**Throughput**	**Location Unaware**	**Packet delivery ratio**	**Residual energy**	**Network lifetime**	**Energy consump-tion**	**Delay/ Latency**
Flat-based routing	AODVI [23]	AODV [62]	√ (-47.6%)	√ (+23.6%)	√	x	√ (+3.6%)	x	√ (DNA*)	x
Location-based routing	ALRP, [26]	HH-VBF [63]	x	x	x	√ (16%)	√ (+16%)	x	√ (DNA*)	√ (-39%)
	Modified Geo. Energy-Aware Routing [25]	LEACH [14]	x	√ (+277%)	x	x	√ (-151.6%)	x	x	x
Hierarchical-based routing	HROCF [29]	FBECS [64]	x	x	√	√ (+17%)	√ (+10%)	√ (DNA*)	√ (-5%)	x
Centralized aggregation	DAHDA [32]	LEACH [65]	x	x	x	x	√ (+ 50%)	√ (+120%)	x	x
	OCCN [22]	HEED [66]	x	x	√	x	√ (DNA*)	√ (DNA*)	x	x
	CCMAR [31]	ECCP [67]	x	x	√	x	x	√ (1.5 times longer)	√ (-12.5%)	√ (-20%)
Distributed aggregation	DA-NUM [40]	SPA [71]	x	x	√	x	x	x	√ (-21.1%)	√ (-30%)
In-Network processing	RINA [44]	AAR [69]	x	x	√	x	x	x	√ (-50%)	x
Proactive routing	CDA [46]	NEECP[56]	x	x	√	x	x	√ (DNA*)	√ (-25%)	x
Reactive routing	DEER [48]	PEP [68]	x	√ (1.6 times more	√	x	x	√ (DNA*)	√ (-50%)	x
	CLUBAA [47]	AODV [70]	√ (-37%)	x	√	√ (+4%)	x	x	X	x
Hybrid routing	SALMA [49]	OLSR [57]	√ (-66%)	x	√	x	x	x	√ (-21.2%)	√ (+16.6%)
Single-Path routing	Mobile sink EE PEGASIS [51]	ECDRA [58]	x	x	√	x	x	√ (DNA*)	√ (-98%)	x
Multipath routing	EESM [52]	SEEM [59]	√ (-29.82 %)	√ (+6%)	x	√(+5.3%)	x	√ (+37%)	x	x
Stationary node-Based routing	CT-RPL [53]	E2HRC-RPL [60]	x	x	x	√	x	x	√ (-13.33%)	√ (-37.5%)
Mobile node-based routing	ZMA [54]	TBID [61]	x	x	√	x	x	x	x	√ (-9%)

Table 3. Limitations of Data Aggregation Techniques

Sr. No	Network Structure	Data Integration Approach	Routing Strategy	Path Establishment	Mobility
1	Flat network structure is inefficient in large-scale networks as all nodes are treated equally, leading to excessive energy consumption for communication.	Centralized aggregation relies on a central node, which, if fails, disrupts the entire network.	WSN nodes are battery-powered, and routing protocols often fail to minimize energy consumption effectively, leading to network lifetime reduction.	If the single path fails due to node failure, energy depletion, or link disruption, the communication is entirely interrupted.	Mobility requires additional energy for node movement, path discovery, and frequent updates.
2	In flat network structure, multiple nodes may transmit redundant data, wasting resources.	Centralized aggregation becomes inefficient as network size increases due to bottlenecks in data processing and communication.	Struggle to handle large-scale networks due to increased complexity in managing routes and communication overhead.	Single path becomes inefficient in large scale networks as it does not distribute the load across multiple nodes.	Continuous topology changes cause delays in establishing and maintaining routes.
3	Static network structures can't be adapted to changes like node mobility or failures.	Distributed aggregation requires extensive communication between nodes for synchronization, leading to energy consumption.	Frequent changes in node availability due to mobility or energy depletion create challenges for maintaining reliable routes.	Overuse of the nodes on the single path, leads to quicker energy depletion in those nodes.	Managing dynamic topology adds complexity to routing algorithms and network maintenance.
4	Forming and maintaining clusters in dynamic networks involves significant overhead and complexity.	In Distributed aggregation, aggregated data may vary due to lack of global knowledge or node failures.	Delays in route discovery or data transmission are common, particularly in reactive protocols, impacting time-sensitive applications.	Maintaining multiple paths, increases communication and computation overhead.	Frequent movement increases the risk of communication breakdowns and dropped packets.
5	Updating location information frequently in dynamic environments can be resource-intensive.	In In-Network aggregation, nodes performing real-time aggregation may consume significant processing power and energy.	Uneven distribution of routing tasks can overload certain nodes, leading to quicker energy depletion in specific areas of the network.	Establishing and maintaining multiple paths can consume significant energy, reducing network lifetime.	
6	Dependency on location information requires accurate position data, often needing GPS or similar technologies, which adds cost and energy consumption.	Using In-Network aggregation, data reduction techniques can lead to loss of fine-grained information.	Many routing protocols are not robust against attacks like data interception, node impersonation, or denial of service, compromising the network's reliability.	Managing and updating multiple paths in dynamic networks adds complexity to path establishment.	

pollution levels and to enable prompt responses to environmental changes or disasters. Through data collecting, WSNs can detect unauthorized movements, intrusions, or other unexpected activity in applications like as home automation, military monitoring, or border security, thereby guaranteeing security and safety. The efficiency of the data collection model impacts the energy consumption, data accuracy, and the network's overall performance. The nodes can transmit data directly to the sink using single-hop communication or through intermediate nodes, aggregator nodes, or cluster head (CH) using multi-hop communication. The primary models for data collection employed in WSNs and their challenges are as follows:

3.1. Random data collection

The random data collection model is a data gathering technique in which data is gathered and delivered at random, non-fixed intervals. As shown in figure 3, sensor nodes use randomized pathways or random intervals to transmit data to the base station or sink, reducing the likelihood of traffic congestion on specific paths. In contrast to periodic models, which transmit data at regular intervals, the random data collection model uses a probabilistic approach or stochastic processes to determine when data should be collected and sent. This model can be helpful in situations where the network needs to balance load and reduce predictability. Since data transmission durations are unpredictable, they can improve network security by making it harder for potential attackers to forecast when packets will be transmitted. This model is ideal for applications where stringent synchronization is not required and data collection is distributed, enabling a more adaptable and energy-efficient approach. Random data collection is used in forest monitoring to collect data on various environmental parameters like temperature, humidity, and soil moisture at random intervals to avoid simultaneous transmissions that could lead to collisions.

Challenges – Random data collection can lead to periods of high data traffic followed by periods of inactivity, which might affect data analysis and aggregation efficiency, and increase in latency. If not properly managed, random collection could lead to the collection of redundant data. Therefore, to guarantee effectiveness and avoid unnecessary data transmission, careful design is required.

3.2. Periodic data collection

This approach involves gathering and sending data at regular, scheduled times. As depicted in figure 4, each node sends its data during a specified time interval to the cluster head and further to the sink node. Node-1 in cluster-1 sends data to the cluster head-1 during the time interval t1 (Dt1), node-2 during the time interval t2 (Dt2), and so on. Similarly, CH1 sends the data during the time interval T1 (DT1) and CH2 sends it during the time interval T2 (DT2) to the next CH3. CH3 sends data during the time interval T3 (DT3) to the base station or sink node. Since the nodes are scheduled for discrete periods, caution must be exercised to reduce transmission delays. As it makes sure that data is collected and transferred to the sink at regular intervals, this model is frequently employed for applications such as environmental sensing, and industrial automation that require continuous and consistent monitoring.

Challenges - In this strategy nodes transmit data even when there are no significant modifications in the sensed environment. The fixed data transmission schedule might not be suitable for dynamic environments where the frequency of events varies over time.

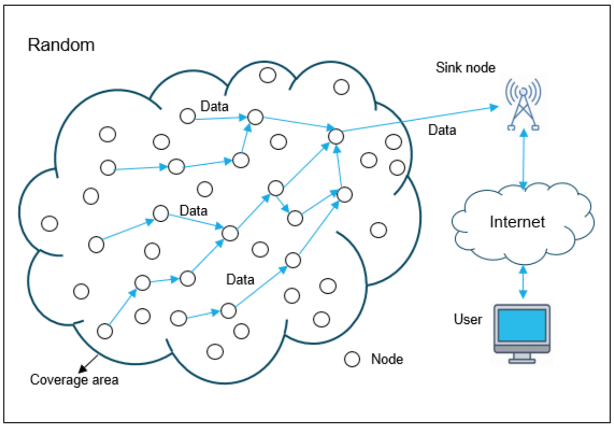

Figure 3. Random

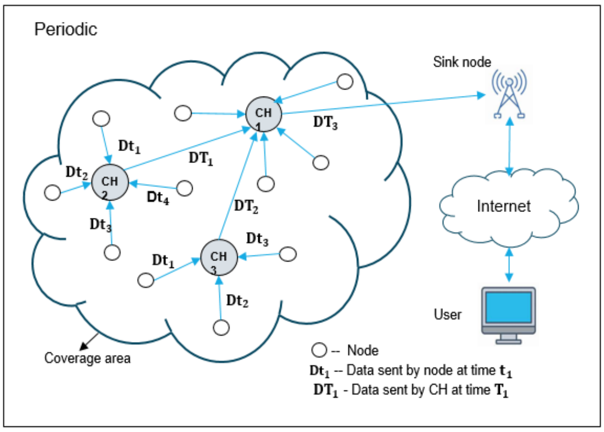

Figure 4. Periodic

3.3. Event-driven data collection

The event-driven data collection model is a technique where data is gathered and sent when only particular events or conditions are identified by the sensor nodes. As shown in figure 5, as soon as the nodes detect an event, they notify the cluster head, and CH sends data to the sink node as required. It saves a significant amount of energy because data is only transferred when needed. This strategy is especially helpful in situations where it is crucial to monitor specific events and take appropriate action instead of gathering data all the time. It is utilized in environmental monitoring to identify abrupt changes in the surrounding environment, including temperature spikes from forest fires or rising water levels from floods. Used for monitoring equipment in the industry to immediately notify issues or threshold breaches to stop damage or downtime.

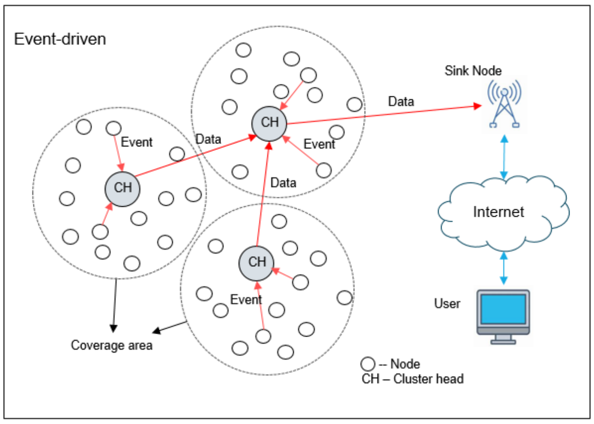

Figure 5. Event-driven

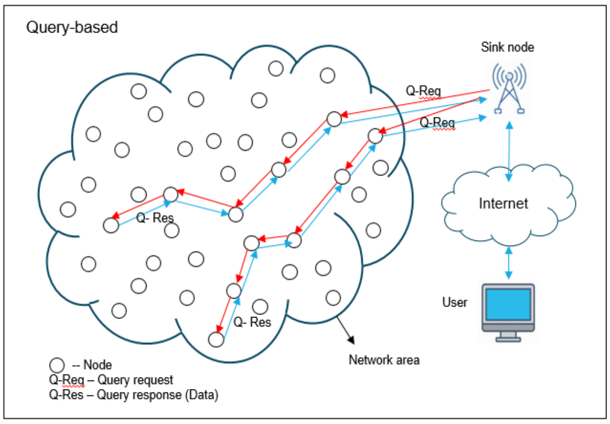

Figure 6. Query-based

Challenges - In the absence of events, data may be sparse which may result in uneven load balancing. Setting up suitable thresholds and event conditions can be difficult and application-specific. False positives or missed events may impact the performance and reliability of the system.

3.4. Query-based data collection

According to this paradigm, data is gathered and sent in response to queries that are specifically sent by a base station. As shown in figure 6, the sink node sends a Query-Request to the specific node, and after receiving the Request message, the specific node transmits the data in Response to the query through multi hop transmission. Queries may focus on specific nodes, regions, or types of data. This selective technique provides the collection of only the required data, hence mitigating extraneous transmissions. The nature of the query request (broadcast or unicast) depends on the specific design, network, and application requirements. As seen in the figure, the sink node sends a query to a specific node using unicast transmission and the node responds to the query by transmitting the data to the sink node. Asset location and status can be monitored using queries in a supply chain or logistics network. After occurrences like earthquakes, engineers might seek particular information about the structural integrity of buildings or bridges.

Challenges - There can be a delay between issuing a query and receiving the data. Hence query-based data collection model is unsuitable for real-time monitoring applications that demand instantaneous data. There may be extra overhead involved in handling and processing queries. The network load may become unpredictable depending on the frequency and complexity of the queries.

3.5. Hybrid data collection

The hybrid data collection strategy leverages the benefits of several data collection methodologies while mitigating their drawbacks by combining their characteristics. It usually combines elements of query-based, event-driven, and periodic data collection approaches, making data collecting more flexible and adaptable. It enables the simultaneous use of multiple data-gathering methods or the option to switch between them. In the hybrid model, by combining event-driven and query-based methods as shown in figure 7, unnecessary data transmissions are minimized when appropriate. It enables continuous data flow and is capable of meeting urgent, real-time data requirements. As seen in figure 4, nodes are intended to identify particular events or conditions (such as threshold levels, and abrupt changes), in the environment and when such events happen, the detecting node instantly sends the relevant information to the CH (as shown with red straight lines). The sink follows up with targeted queries to gather more detailed information indicated by Q-Req (Query request as shown in red curved lines). The response to queries i.e. sending the relevant data is indicated by Q-Res (Query request as shown by blue lines). Applications where flexibility and extensive data coverage are critical, such as industrial automation, smart agriculture, healthcare, and environmental monitoring, are ideally suited for the hybrid approach.

Challenges - In this approach, complex algorithms are needed to effectively integrate and transition between various data collection techniques. More memory and computational power on sensor nodes might be needed which is challenging in energy-constrained nodes. Additionally, it requires careful coordination to guarantee that, combined data collection techniques work in concert rather than against one another.

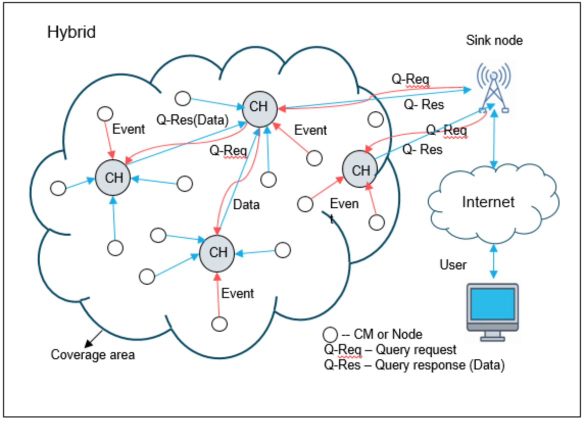

Figure 7. Hybrid

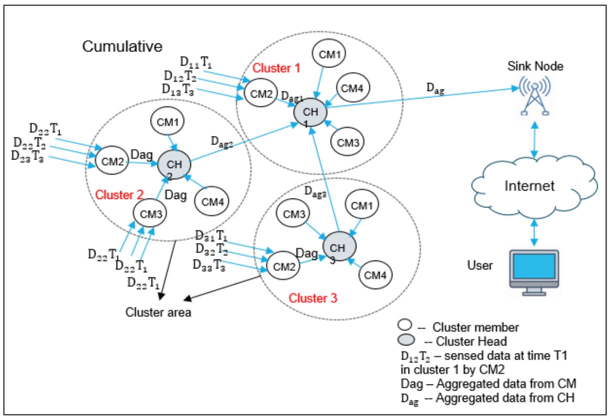

Figure 8. Cumulative

3.6. Cumulative data collection

This is a method where data is delivered after being compiled over time. As depicted in figure 8, cluster member-2 of cluster1 senses the data at various time intervals T1, T2, and T3 aggregates this data (Dag), and transmits it to CH1. CH1 aggregates data (Dag) from its cluster members and sends the aggregated data from all cluster heads to the sink node. Rather than transmitting individual data readings immediately, sensor nodes gather data over time, process it, and then transmit the combined data that reflects the behaviour of the monitored environment. This model minimizes the amount of transmissions to save energy and reduce communication overhead. It is advantageous for applications where detailed, high-frequency data is not required. The cumulative model is well-suited where long-term trends are more important than real-time data, such as climate monitoring. It is used in applications where aggregated data can provide insights into average temperature, humidity, or pollution levels over time.

Challenges - In this approach, aggregating the data over time may cause a loss of detailed information which may affect the accuracy of the received data. Data availability is delayed by the model since data is only transmitted after aggregation. It demands striking a balance in the trade-off between data granularity and transmission efficiency.

4. Directions for Future Research

The following lists some of the gaps in the current data aggregation methods, which may provide direction in the key areas for future research.

4.1 Optimal bandwidth utilization and energy

A high node density can result in more nodes competing for the same wireless media, which would limit each node's available bandwidth because of retransmissions and collisions. Frequent retransmissions of data utilize considerable amounts of energy. Some nodes may become bottlenecks due to non uniform distribution, which will decrease their effective bandwidth. Bandwidth usage is affected by periodic, event-driven, or continuous traffic patterns. Bursts caused by event-driven traffic may temporarily restrict available bandwidth.

Nodes can avoid congested channels and maximize bandwidth utilization by using Cognitive Radio Networks (CRNs) to automatically choose transmission frequencies based on real-time spectrum analysis. Predictive Models using Machine learning techniques can be used to regulate node behaviour to reduce energy consumption by forecasting future network conditions. By implying Reinforcement Learning (RL), nodes can interact with the environment to learn optimal energy management strategies, to continually enhance energy efficiency. Applying the RL technique, the node can monitor its environment, considering parameters such as network traffic, neighbouring node states, residual energy, etc., to determine its present condition. Further, the node can update its policy using the observed reward such as efficient energy consumption, successful data transmission, or network lifetime improvement and the new state information. For this, algorithms such as Q-learning and Deep Q-Networks (DQN) can be used.

4.2. Energy-efficient scheduling

Nodes modify their duty cycles in response to energy levels, environmental conditions, and traffic demand in real-time on the network. Adaptive Energy-Efficient MAC (AEEMAC) algorithms alter duty cycles dynamically in order to maximize both performance and energy consumption. In ideal scheduling, every node should get a chance to sleep, based on its residual energy. In real-time, it is difficult for every node in the network to enter into a sleep state, specifically the nodes around the sink node. For the nodes close to the sink node to transmit data to it, they must continue to be active. A bottleneck caused by heavy traffic load near the sink causes these nodes to use energy much more quickly than nodes that can sleep, which shortens the network’s lifespan. Most MAC-based protocols have inaptly imposed SYNC control messages that control the duty cycles. As a result, even in the absence of a signal, a node is forced to remain awake. If the nodes in the network intelligently coordinate their sleep patterns, there can be significant energy savings in large WSNs. Overhead may be incurred when nodes are kept in sync to facilitate coordinated sleep-wake cycles.

We propose to utilize Machine learning algorithms that can predict future traffic patterns and accordingly adjust duty cycles. By using past data, algorithms such as Reinforcement Learning (RL) and Deep Learning (DL) can optimize duty cycles. Nodes can be equipped with energy harvesting capabilities to modify their duty cycles based on the availability of environmental energy sources such as wind, sun, etc.) thereby reducing the dependency on battery power. Cooperative MIMO (Multiple Input Multiple Output) techniques can be used to enable several nodes to collaboratively transmit data, decreasing the energy consumption of individual nodes and minimizing the active periods necessary for communication.

4.3. Assessment of residual energy

Routing protocols that are energy-efficient take into account both the nodes’ residual energy and the energy consumption for communication. Nodes work together to communicate and share data to estimate each other’s residual energy. The network’s energy information is compiled using methods like distributed consensus protocols and gossip algorithms. Certain data aggregation techniques, such as PEDAP, HEED, LEACH, and PEGASIS, implicitly assume that each network node’s residual energy is known beforehand. This assumption is far from reality, and these techniques are based on cluster head selection. It is quite challenging to simulate the energy consumption pattern of the diverse heterogeneous devices in the network. Large wireless sensor networks cannot have their node residual energies determined by models that attempt to use the state information on control packets.

We suggest the use of Regression algorithms and neural networks to estimate the residual energy based on node activity, energy consumption patterns, and environmental conditions. To maximize node longevity and performance, Q-learning algorithms can be used to dynamically modify energy consumption techniques based on the estimated residual energy levels.

4.4. Efficient data aggregation

Multiple sensor nodes monitoring the same event can generate redundant data, which aggregation techniques must handle to avoid needless processing and transmission. Before aggregating, data is reduced in size using techniques including wavelet-based compression, Huffman coding, and run-length encoding (RLE), which saves energy during transmission. Nodes efficiently sample and collect data using compressive sensing algorithms, which minimizes the number of transmissions required. By employing signal sparsity, this technique can reconstruct data using fewer samples. It is often difficult to aggregate correlated or redundant data while maintaining the quality and integrity of the aggregated result, and advanced algorithms may be essential.

To reduce the number of data transmissions to the base station, machine learning models with Edge Intelligence can be installed at edge nodes or gateways to perform real-time data aggregation and analysis. These models can find trends and abnormalities locally.

4.5. Data diversity and diverse node capabilities

Different forms of data, such as numerical, categorical, multimedia, etc., may be collected by sensor nodes, which makes it challenging to aggregate and interpret the data uniformly. Collecting data from many sensor-node types, such as humidity, temperature, and mobility, necessitates the use of complex fusion algorithms that can handle a wide range of formats and standards. Large computing resources are frequently needed to aggregate diverse data, and these resources may be limited on power-constraint sensor nodes. Different sensors might have varying levels of accuracy, precision, and reliability, leading to potential inconsistencies. It can be difficult to develop uniform aggregation methods since heterogeneous nodes inside a WSN may have varying processing capacities. The employment of diverse communication protocols by heterogeneous nodes might make the integration of data more difficult. The major challenge is that the diverse data sources might introduce noise and outliers, which may complicate the heterogeneous data aggregation process and may result in inaccurate interpretations.

We suggest using normalization techniques such as FST (Feature Scaling Techniques) like min-max scaling or z-score normalization to transform disparate data formats into a common scale or format, facilitating the aggregation of data from many sources. To fuse data from multiple sources, for example, convolutional neural networks

(CNNs) for multimedia data and recurrent neural networks (RNNs) for time-series data can be used. Noise can be eliminated from heterogeneous data collection in resource-constrained wireless sensor nodes by using the Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF), which can handle non-linear systems and many types of measurements. The Kalman filter's ability to handle data in real time is vital for applications that need to respond immediately. The EKF or UKF adapts dynamically to changing noise levels and sensor readings by modifying its parameters in response to the incoming data. It uses smaller state-space models or approximations to reduce memory utilization. For sensor nodes with limited resources, the Kalman filter may need computationally demanding matrix operations like multiplication and inversion. To minimize computing load, we can use fixed-point arithmetic instead of floating point arithmetic or simplify the mathematical operations in the method. Designing the filter in a distributed manner can also aid in reducing the computational burden across multiple nodes. Simplified Kalman filter variants, like the Alpha-Beta or complementing filter, can offer a favourable trade-off between performance and resource consumption for nodes with severe resource constraints.

4.6. Intelligent data sampling

Regulating the data sampling rate is necessary according to the demands of a particular application, the data's unpredictability, or the surrounding environment. To conserve energy, the sample rate can be lowered during times of minimal change and raised when more notable changes are found. When certain events or circumstances occur, including motion detection, abrupt temperature changes, or crossing threshold, data should be gathered in response. This guarantees that, in the event of noteworthy occurrences, only pertinent data need to be sampled. Intelligent data sampling prolongs the lifetime of the network by preventing superfluous data collection and transmission, which lowers the energy consumption of sensor nodes. It optimizes the time and node selection for data gathering to effectively and efficiently cover the area of interest and hence reduces data traffic, easing network congestion, and enhancing communication efficiency. Selective data collection can reduce data volume while preserving essential information. This can be achieved by establishing a threshold for certain parameters and only gathering data when these are exceeded. The rate and duration of the data collection process have an impact on the accuracy and comprehensiveness of the dataset.

It might be difficult, particularly in dynamic contexts, to ensure synchronized collection of data across distributed nodes. The system needs to be sufficiently adaptable to alter and learn continuously to meet the ever-changing requirements and conditions. This adaptability can be achieved through a combination of advanced techniques and strategies such as Collaborative and Distributed Learning, Real-time processing, Predictive models, and Feedback mechanisms. We suggest utilizing Edge Computing to process data locally at the sensor node level and eliminate the need for constant communication with the base station. Through collective intelligence, nodes can be made to share insights and learned models, increasing the network's overall adaptability. Create predictive models by utilizing past data that anticipate future circumstances and make proactive adjustments to sampling strategies. To adapt operations dynamically, implement feedback mechanisms whereby sensor nodes report their status, such as battery life, data quality, etc.

4.7. Integration with emerging technology to ensure low-latency and privacy

Timely data aggregation can be impacted by variations in network delays. The total latency can be increased by processing delays at nodes with insufficient computational power. The amount of data that needs to be aggregated grows as the number of nodes does, which could result in higher latency. Excessive data flow can cause network congestion, which raises delay even more. As data volume increases, it might become more difficult and heavy on resources to make sure that data is anonymized before being aggregated to preserve privacy.

To aggregate data in WSNs efficiently and maintain low latency and privacy, Machine Learning, Artificial Intelligence (AI), Edge and Fog Computing, Advanced Networking Technologies, and Encryption Techniques can be integrated. To minimize latency, implement Edge and Fog Computing to execute data processing and aggregation closer to the source node and to ensure privacy, use effective privacy-preserving strategies, such as anonymization and lightweight encryption. To guarantee data integrity and security during aggregation, we suggest the use of Blockchain Technology to produce unchanging records of data interactions. Further efforts and standardization are needed to ensure interoperability between various Blockchain platforms and WSN protocols. Blockchain guarantees data integrity, but it does not by default guarantee data confidentiality. Sensitive data must be protected with additional encryption, which might increase complexity and overhead. Lightweight Blockchain solutions that require less storage and processing power can be created, such as mini-Blockchains or DAG (Directed Acyclic Graph) structures. Additionally, we propose to implement SDN (Software Defined Network) to dynamically manage network resources and optimize data flow, lowering latency, and providing network-level security policies to safeguard data during aggregation with the incorporation of 5G technology.

4.8. Dynamic network topology

Data aggregation is made more difficult in networks with mobile nodes because of the frequent changes in network structure. It is difficult to guarantee smooth handoffs and ongoing data aggregation while nodes are in motion. Links can break and re-establish themselves due to mobile nodes or nodes with varying energy levels joining and leaving the network repeatedly. This interferes with the current routes for data aggregation. Route discovery and maintenance must be done constantly due to topology changes, which may increase latency, energy consumption, and overhead. Packet loss can be caused by unstable connectivity and frequent disconnections, which lowers the accuracy and comprehensiveness of aggregated data.

We propose to utilize machine learning algorithms to forecast changes in topology by using past data. This would enable the network to make proactive modifications to its routing and aggregation schemes. An algorithm can be designed to maintain numerous routes to the sink node so that data loss and delay can be minimized by promptly activating a backup route if a primary route fails due to changes in topology. It is possible to employ threshold-based clustering algorithms, in which nodes enter or exit clusters according to predetermined energy thresholds. A new cluster head is chosen when the energy of a CH falls below a predetermined level.

4.9. Cross-Layer Optimization

In the traditional layered approach in WSN, there is limited interaction between layers, and each layer functions independently. Because a layer may not have access to pertinent information from other layers, this separation may result in decisions that are not as effective as they may be. The network layer, for instance, might select a route that is best in terms of hop count, but it ignores the nodes' energy level, which is controlled by the physical layer. This can cause some nodes to lose energy more quickly than others, shortening the network lifetime. The conventional layer model makes inefficient use of resources like energy, bandwidth, and processing power since it does not permit coordinated management of these resources across levels. For instance, a node may expend energy by retransmitting data needlessly, managed by the MAC layer, while the application layer could accept a small amount of packet loss without impairing the performance of the application as a whole.

The drawbacks of the traditional layer approach are mitigated by Cross-layer design, by facilitating communication and information sharing between layers to maximize overall network performance in resource-constrained WSNs. In the Cross-layer approach, the network layer and the physical layer may share channel characteristics, enabling the routing protocol to select routes that minimize energy usage or prevent interference. It is possible to optimize power regulation (physical layer) and routing (network layer) in unison to minimize energy usage and preserve acceptable communication quality. According to the demands of the application layer, the MAC layer may modify its duty cycling, saving energy during periods of low activity. Rather than optimizing each layer separately, the cross-layer design optimizes many parameters (e.g., delay, throughput, reliability) simultaneously, which can result in improved overall network performance.

Implementing and managing cross-layer designs becomes more difficult since interactions between layers must be thoughtfully planned to prevent conflicts and guarantee consistent performance. Cross-layer design improves performance, but it also makes layers more dependent on one another, increasing the network's susceptibility to cascade failures or poor performance if one layer malfunctions.

4.10. Environmental Sustainability

WSNs are widely utilized in many different environments and in large quantities, therefore it is imperative to consider how their design, deployment, and maintenance may be done in an environmentally conscious manner. If nodes are not made to last or be reused, the widespread usage of WSNs may produce a considerable amount of e-waste. The carbon footprint is increased by the manufacture, installation, and use of WSNs. This effect can be minimized by utilizing sustainable materials and consuming less energy. The use of packaging and sensor enclosures made of biodegradable materials can lessen the long-term environmental effects. Sustainable or biodegradable materials are that materials decompose organically in the environment and are known as biodegradable polymers that can lessen the long-term waste produced by sensor nodes. The casing and packaging of sensor nodes can be made of a biodegradable plastic like Polylactic Acid (PLA) which is produced from renewable resources like sugarcane or corn starch. Eco-friendly sensor packaging can make use of polyhydroxyalkanoates (PHA), a type of biodegradable plastic made by microbial fermentation.

Energy-constrained WSNs can benefit greatly from long-range communication provided by low-power wide area networks (LPWAN) such as Sigfox, LoRaWAN, and NB-IoT thereby extending the network's lifetime.

Avoiding over-deployment by just deploying the minimal number of nodes required to attain the targeted coverage and data accuracy can reduce the overall environmental impact. In outdoor applications, in particular, small solar panels can be embedded into sensor nodes to capture sunlight and lessen dependency on batteries. The use of organic semiconductors made from carbon-based materials can be potentially more sustainable than traditional silicon-based semiconductors. The carbon footprint of WSNs can be greatly reduced by utilizing recyclable, renewable, and biodegradable materials as well as energy-efficient and sustainable power sources, all of which will help to achieve broader environmental sustainability objectives.

5. Conclusion

The purpose of the study is to give the reader a brief introduction to the methods of data aggregation and aggregation protocols that are currently in use. Knowing which data aggregation technique to implement for a given application is crucial since data aggregation extends the life of WSN. We have emphasized the challenges in data aggregation and routing mechanisms. A tabular summary of the comparison of various data aggregation algorithms enables appropriate algorithm selection based on several performance evaluation matrices. We have discussed the competing requirements and trade-offs required to optimize several resources, such as residual node energy, communication bandwidth, computation overhead, latency, data accuracy, network longevity, and energy usage, which have been thoroughly discussed. We have identified the research gaps in the present literature, which could point future researchers towards the key areas of data aggregation.

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