Rapid Data Transmission Technique through Tree Generation & Event Aggregation to Achieve Low Latency & Energy Saving in Wireless Sensor Networks

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Computer/IT Engineering

by

Jani Raxit Girishkumar
179999913026

under supervision of

Dr. Ramesh T. Prajapati
Professor, Shree Swaminarayan Institute of Technology, Bhat, Gandhinagar - 382428

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

September 2026

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ABSTRACT

Wireless Sensor Networks (WSNs) have been indispensable elements of various technological systems in recent years, offering applications such as environmental monitoring, smart cities, industry automation, and healthcare. WSNs are made up of many sensor nodes that perform functions such as sensing, processing, and sending sensed data to the base station in the network. Nevertheless, due to the nature of WSNs and the presence of constraints like limited energy, computing ability, and limited bandwidth, efficient data transmission in wireless sensor networks has become difficult to achieve. One of the main challenges facing researchers nowadays is finding a balance between energy-efficiency and low latency since they conflict with each other.

The current study is aimed at proposing a method for fast data transmission that takes into consideration both energy-efficiency and latency aspects in WSNs. The key difference between the current approach and the previous ones is the importance given to latency since in most cases studies have focused mainly on minimizing energy consumption. After building the aggregation tree, one of the most important steps of the current approach is the data aggregation technique, whereby the sensor readings collected from different sensors are packed in one packet.

Apart from data aggregation, this paper proposes an event aggregation technique, whereby the initial data is transformed into events that will facilitate fast and efficient data transmission process. In order to increase efficiency, the framework proposes the implementation of a combination of centralized and distributed scheduling methods together with intelligent scheduling algorithms that will avoid packet collision in the transmission channel. The use of these two techniques enhances efficiency by ensuring optimum allocation of time slots, thus enhancing the throughput of the network and minimization of transmission delays. Fault tolerance, such as retransmission, replication, and signal quality measures like RSSI and LQI have been included in this framework.

These proposed concepts have been tested using simulations in standard platforms such as Castalia and NS2 to show how effective they work. Through these simulations, the results

show marked improvements in latency times, energy conservation and scalability of the network as compared to traditional techniques like LEACH and CTP.

As further proof of the practical nature of the solution, the development of a prototype is carried out through the implementation of a wireless network that involves gas detection as its main application area. This system is designed to acquire data, transmit it, and analyze it in the cloud environment, confirming the practical applicability of the proposed framework.

To summarize, the conducted research offers a powerful and effective approach towards implementing efficient communication in Wireless Sensor Networks via tree-based communication, aggregation of data, and intelligent scheduling strategies.

Dedicated to
My Father

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I am deeply grateful to my wife Charmie, without whose constant support and understanding this achievement would not have been possible. Everything I achieve is often a manifestation of a dream she envisioned for me years ago. My parents' unwavering trust in my abilities often surpassed my own self-belief, driving me to push my limits. My father's lessons on working smartly, systematically, and professionally, coupled with my mother's strength, perseverance, and never-give-up attitude, have been my pillars of support. Their insights have greatly enhanced the quality of my research.

Balancing a job and a Ph.D. was a challenging endeavour, but watching my dear friends and colleagues handle multiple responsibilities with grace and dedication inspired me to stay focused. Their support in managing day-to-day challenges has been invaluable. I am also incredibly grateful for their constant encouragement and understanding. Their presence added joy and stability to my life, helping me navigate the challenges of this journey with encouragement, shared laughter, and unwavering emotional support. The shared camaraderie made this experience more enjoyable and memorable.

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Table of Contents

List of Abbreviations

1. AC: Available Channels
2. BA: Branch Access
3. BFS: Breadth-First Search
4. CDS: Connected Dominating Set
5. CMST / CMS: Capacitated Minimal Spanning Tree
6. CS: Communication Set / Candidate Set
7. CTP: Collection Tree Protocol
8. DAS: Data Aggregation Scheduling
9. DBEA: Delay Bounded Event Aggregation
10. EAS: Event Aggregation Scheduling
11. FTSP: Flooding Time Synchronization Protocol
12. GS: Growth Set
13. ICT: Information and Communications Technology
14. IEEE: Institute of Electrical and Electronics Engineers
15. LEACH: Low-Energy Adaptive Clustering Hierarchy
16. MAC: Media Access Control
17. MIS: Maximal Independent Set
18. MMSN: Multi-Frequency Media Access Control
19. NP: Nondeterministic Polynomial time
20. PG: Potential Growth
21. Rx: Receive / Receiver
22. SINR: Signal-to-Interference-plus-Noise Ratio
23. SNR: Signal-to-Noise Ratio
24. SS: Search Set
25. TDMA: Time Division Multiple Access
26. TDMA: Time Division Multiple Access
27. TMCP: Tree-based Multi-Channel Protocol
28. Tr: Transmit / Transmitter
29. TST: Time Slot to Transmit
30. WSN: Wireless Sensor Network

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CHAPTER – 1

Introduction

In the last couple of decades, WSNs have gained much popularity because of their various practical uses in fields like industry control systems, health care, military applications, smart cities, and environmental monitoring. In a wireless sensor network, many sensor nodes are distributed randomly in a certain geographic area, which is able to sense any environmental information and then communicate with other sensor nodes as well as forward the gathered information to a centralized base station or sink node [1]. However, although WSNs have many benefits, they face several restrictions due to their nature, including having limited energy sources, communication bandwidth, and computing power [11, 48]. Therefore, efficient transfer of data from sensor nodes to the base station becomes one of the main issues in the field of WSN design. Because sensor nodes have limited energy supplies and can be located in inaccessible regions, it is not possible to change or recharge batteries [4, 52].

One of the popular approaches used in WSN for communication is called convergecast, whereby multiple nodes sense data and send it to one single node referred to as sink node. Convergecast is achieved through multi-hop communication approach that involves forwarding data from other nodes by intermediate nodes to the base station [. While convergecast enables an efficient method for collecting data, there are a number of problems associated with the approach, such as excessive energy usage, duplicate data transmissions, collision of packets, and latencies. Some of the ways of solving energy issues include use of data aggregation technique, where data packets from other packets are aggregated into a single data packet. Besides, routing algorithms have been developed to reduce the cost of communication [2, 12].

Nevertheless, with the appearance of new applications, such as real-time monitoring systems, disaster management applications, and IoT based environments, the needs of WSNs have changed significantly. While the main goal is still the energy-efficiency, another feature that is required today is the ability to transfer data with minimal delay. This feature becomes extremely important for many applications like gas leakage detection systems or health monitoring systems because delay in data transmission could bring serious consequences [3, 40]. Latency is not the only issue that should be taken into account when designing a new-generation WSN because of network congestion, packet collision, and ineffective scheduling algorithms decrease its performance even more [10, 50]. Multiple simultaneous data transmission results in increased interference and requires retransmission, hence causing an increase in the energy spent. Thus, the creation of an optimal trade-off between energy-efficiency and latency has turned out to be one of the primary goals today [5, 90].

The current research is directed at the development of integrated solutions combining tree-based data organization, data aggregation, event-based processing, and smart scheduling mechanisms [41, 80]. It means that tree-based organization helps to optimize the data transmission process, while event-based processing allows reducing the number of useless data transmissions, which makes smart scheduling algorithms more effective [6, 13].

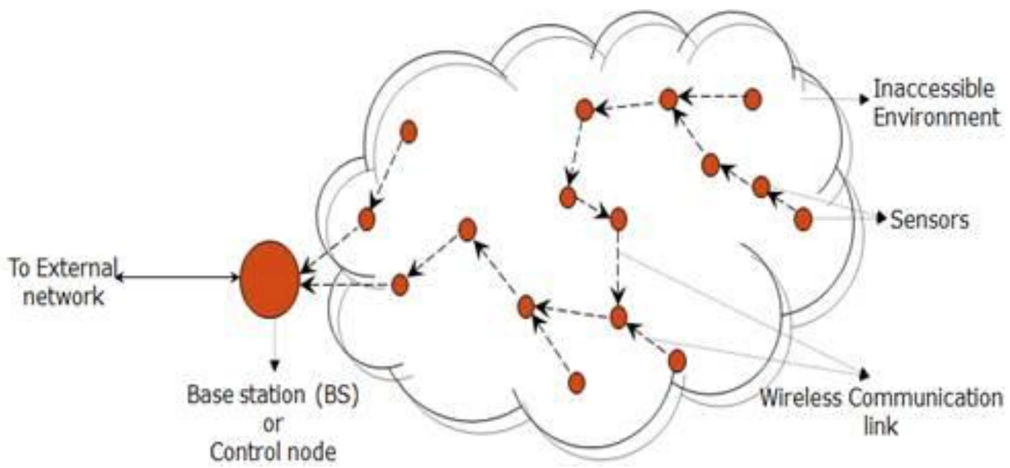


Figure 1 Basic Convergecast Communication in Wireless Sensor Networks

1.1 Event Aggregation in Wireless Sensor Networks

Event aggregation is a powerful enhancement of data aggregation developed especially to ensure fast and efficient data transmission in Wireless Sensor Networks (WSNs) [30, 79]. Specifically, in terms of the above-mentioned study, event aggregation is an important aspect as far as it allows improving the operation of WSNs through the reduction of communication overhead, at the same time providing low-latency data transfer [7,21]. As opposed to data aggregation, which involves the process of merging multiple readings into one data packet, event aggregation implies a smart procedure during which raw data is analyzed and transformed into application-level events.

It is especially significant today since, as mentioned above, it is rather unnecessary and inefficient to have continuous streams of raw readings coming from different sources [8, 31]. First of all, it increases the amount of energy that is required for data transmission. Moreover, it leads to packet collisions as several sensor nodes might try to communicate their reading at once, resulting in network congestion. It is especially important for the above-mentioned study because it is devoted to the development of a smart indoor environment monitoring system in which energy consumption is one of the main concerns [9, 50].

One of the ways through which event aggregation helps in solving the above problems is the transfer of some of the burden of data handling to the individual sensor nodes. Rather than transmit any sensed data without analyzing its significance, the sensor node analyzes the data locally based on predetermined criteria such as comparison of values to thresholds [10, 78]. An event occurs where there is a drastic change or significant criteria is met, and transmission begins.

For instance, in a case where an event aggregation is used in a gas sensing application using the MQ7 sensor [89], instead of continuously transmitting gas concentration levels at every time interval, the sensor creates and transmits the following critical events:

- "Gas concentration exceeds the threshold"
- "Air quality dangerous"

By reducing the amount of redundant data being sent, the proposed event-driven communication technique drastically reduces communication loads within the network [55, 79]. The reduction in number of transmissions also means reduction in energy use and an increase in network lifespan. Moreover, since less transmission takes place at once, the chances of collision are greatly decreased, making communications more reliable and efficient [12, 81, 98] .

Yet another benefit of event aggregation comes from latency improvement. In essence, by sending only the relevant data, network congestion is kept low [75, 88]. This means that critical information can be delivered faster. For applications requiring immediate response, this is crucial, because a delay in communication may result in a disaster [14, 100]. Event-based transmission of relevant information makes it possible to guarantee fast and efficient information exchange when required.

In addition, using an event aggregation technique will help to scale the network. Without any aggregation, an increase in the number of network nodes would mean a corresponding increase in the amount of information transferred through the network. This would make it harder to control the system.

First, event-based communication significantly decreases unnecessary data transfer, thus reducing the overall communication burden on the network. With less transmission going on, energy consumption decreases along with network life span increase. Moreover, there are no chances of overlapping data streams when they occur, and therefore reliability of communication becomes much better because of lower probabilities of packet collision.

Next, there is one more significant advantage of using event aggregation in our system - reduction of latency levels in the network. Latency is reduced because the only meaningful information is transmitted via the network. Such feature becomes especially important in cases of real-time applications where any delay in transmission can have extremely dangerous effects. Therefore, we can be sure about timely data transmission.

Finally, the last advantage of using event aggregation is improvement in scalability. If the number of devices grows, then there will inevitably be more raw data transferred between

nodes. Event-based approach allows to control the amount of generated data and not let it grow disproportionately.
Overall, the process of event aggregation converts the conventional method of data transmission in wireless sensor networks into an intelligent event-based mechanism. This, apart from improving the energy efficiency and lowering the latency, makes the whole system more reliable and scalable as well.

1.1.1 Need for Event Aggregation

The use of event aggregation in this study was inspired by the limitations seen in conventional convergecast and data aggregation methodologies that mainly consider energy consumption without regard to latency and scalability issues.

The main benefits behind the use of event aggregation in the system proposed are:

- Reduced Redundancy in Data Transmissions:
  This is due to the fact that in dense WSN networks, several sensors may be detecting similar information about the environment. This creates redundant transmission of data which is wasteful of bandwidth.

- Minimized Energy Consumption:
  Communication in WSN is one of the operations that require the highest energy consumption. Since fewer transmissions mean lesser energy consumed, it will extend the operational life of the network.

- Less Latency:
  Fewer data packets will result in less congestion and thus faster transmissions. This is especially important for delay sensitive applications like environmental and hazard monitoring.

- Scalability Improvement:
  As proven in the simulations conducted, this technique can easily operate with both small networks consisting of around 50 nodes and big networks of up to 15000 nodes.

- Increased Bandwidth Efficiency:
  By sending event data only, channel contention is minimized hence maximizing channel capacity.

1.1.2 Working Principle of Event Aggregation

The process of aggregation in the proposed architecture works in an organized way, which involves the use of routing and scheduling along with trees. This makes sure that efficient data processing takes place and helps in transmitting data effectively.

The working process can be described as follows:

1. Sensing Phase:
   Sensors keep on sensing various parameters related to the environment, such as gas concentration, with the help of MQ7 sensors. Data collection occurs regularly and is used for processing.

2. Local Processing Phase:
   Data obtained is processed locally in each node and compared with some threshold value. Centralized processing is not required in this phase.

3. Event Generation Phase:
   If the data sensed is more than the threshold value, an event is generated. Here, only those events are generated which are of significance for further transmission.

4. Aggregation Phase:
   The events generated in the previous stage by different nodes are collected by the dominator nodes in this phase and aggregation is done. The formula for doing aggregation is:

   $$f(A_w, X_1, X_2, \dots, d)$$

   where A_w is the data obtained by the node itself and $X_1, X_2, \dots, d$ are the data obtained by its child nodes.

5. Transmission Phase:
   Aggregated data is transmitted from one level to another in the hierarchical tree-like structure till it reaches the sink node.

1.1.3 Event Aggregation Model

Event aggregation will not be developed as an independent mechanism but rather will be deeply embedded within the overall architecture of the system, incorporating routing, aggregation, and scheduling.
This event aggregation framework will be founded upon the following essential elements:

- Tree-Based Routing Framework:
  The BFS-based aggregation tree will be built to facilitate communication effectively, minimizing hops and delays.

- Dominator-Dominatee Structure:
  The nodes will be classified into two categories: dominators and dominatees. The dominatees will relay their data to the dominating nodes, which will aggregate the information and then transmit it up the dominance chain.

- TDMA-Based Scheduling:
  Time slots will be allocated to the nodes to prevent any collision and allow efficient communication.

Characteristics of the Model:

- Partial Aggregation:
  The model permits delay-bounded aggregation, such that nodes can send information even without successful completion of full aggregation within the stipulated time frame.

  - Hierarchical Aggregation:
    Information is transmitted in a hierarchical manner, starting from leaf nodes up to dominator nodes before reaching the root node (center of topology).

- Event-based Communication:
  Transmission of data happens only upon detection of major events.

1.1.4 Impact of Event Aggregation on Proposed System Performance

It is worth noting that event aggregation greatly contributes to the improvement in the performance of the proposed system, as confirmed by simulations.

- Energy Efficiency:
  Through the reduction in transmissions, the proposed system minimizes the amount of energy required for operation. An average value of energy consumption per node has been determined to be 2.345 Joules, which is less than other methods have shown.
- Latency Reduction:
  As a result of decreased network congestion and proper scheduling, latency levels are significantly reduced in the proposed scheme (averaging 150 ms).
- Scalability:
  The performance of the system remains constant regardless of the size of the network, thus, proving the system's scalability (the test was carried out on networks consisting of 150, 1500, and 5000 nodes).
- Minimized Collisions:
  As a result of lower amounts of packets being transmitted, the number of collisions is minimized.

It is concluded that event aggregation is an effective method that can be used to transmit data rapidly in WSNs.

1.2 Centralized Tree-Based Protocols and Algorithms

Centralized tree generation algorithms have proven to be effective for enhancing the data transmission process in WSNs. Under this technique, the wireless network will be organized hierarchically [58, 69]. Specifically, a structured hierarchy will be used for organizing the data flow process, whereby the tree will start with the sink node and will have data flowing from different sensor nodes towards the sink node. However, unlike distributed techniques, in the case of centralized tree algorithms, it is assumed that there is prior knowledge by the sink node or controller on the topology of the network [84, 96].

The most important strength in using centralized tree algorithms is that they help minimize redundant transmissions, minimize interference during data transmission, and enhance network coordination as a whole. For example, through building an optimized tree for aggregating data, data can be passed through the appropriate path with minimized hops and interference. Centralized scheduling techniques may also be used to schedule the transmissions effectively without causing any interference [15, 55, 87, 90].

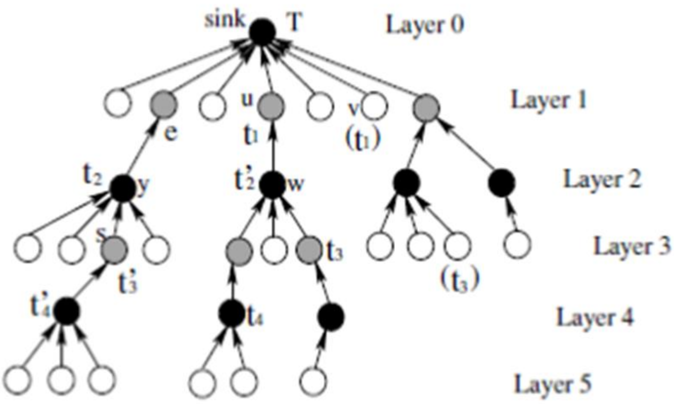


Figure 1.2 Reconnect domenetees

Nevertheless, although centralized protocols offer various benefits, the majority of current algorithms concentrate solely on certain aspects such as energy conservation, dependability, or synchronization, neglecting the necessity of fulfilling both low-latency and energy-efficient conditions. Furthermore, the vast majority of contemporary centralized protocols fail to implement event-driven aggregation procedures, which is critical for today's applications requiring real-time information. Thus, although centralized tree-based approaches serve as a solid basis for efficient data transfer, there remains a requirement for an innovative solution, such as that proposed in this study, which incorporates tree construction, event aggregation, and smart scheduling techniques.

The following sections briefly introduce a number of popular centralized tree-based protocols utilized in this study.

1.2.1 LEACH (Low-Energy Adaptive Clustering Hierarchy)

LEACH stands for Low-Energy Adaptive Clustering Hierarchy, and it is among the most successful hierarchical routing protocols devised particularly for improving the energy efficiency of WSNs [56, 61]. The key contribution of LEACH lies in the idea of clustering, wherein the whole network is segmented into different clusters. Every cluster comprises different sensor nodes and a special node termed as the Cluster Head (CH).

The basic principle of LEACH protocol is to reduce communications between the sink and sensor nodes directly since transmission over long distance is extremely power consuming [76, 81, 65] . However, through the use of LEACH protocol, the sensor nodes transmit their data to the cluster head, and then the data is aggregated by the cluster head and then transmitted to the sink.

Working Mechanism of LEACH

LEACH operates in rounds, and each round is divided into two major phases:

1. Setup Phase (Cluster Formation Phase)

This phase is responsible for the formation of clusters and the selection of cluster heads.

- Each node independently decides whether to become a cluster head based on a predefined probability P.
- A random number between 0 and 1 is generated by each node.
- If this number is less than a threshold value $T(n)$, the node elects itself as a cluster head.

The threshold is defined as:

$$T(n) = \{\frac{P}{1-P\times(r\ MOD\ \frac{1}{P})}, IF\ n \in G;\ 0, otherwise$$

Where:

- P = desired percentage of cluster heads
- r = current round
- G = set of nodes that have not been cluster heads in the last $\frac{1}{P}$ rounds

When chosen:

- The cluster heads will advertise through a message known as ADV to other nodes.
- All non-cluster heads will select a cluster head with the highest strength of signals (least communication cost).
- All nodes will send a message known as JOIN-REQ to the selected cluster heads.

Following cluster creation:

The cluster heads develop a TDMA timetable and allocate time slots for all member nodes.

2. Steady-State Phase (Data Transmission Phase)

This phase takes care of sensing, aggregating, and communicating data.

- All the nodes communicate sensed data to their respective cluster heads in their assigned TDMA slots.
- Sleeping mode is used for those nodes that do not transmit data; thus, energy is conserved.
- Data aggregation is done by the cluster head to avoid any redundancy of data.
- Aggregated data is transferred to the sink node in one hop.

This process goes on for a fixed period before the next cycle starts.

Features of LEACH Protocol

- Cluster-Based Network Structure:
  Divides nodes into small groups to simplify network management.

    - Cluster Head Rotation Mechanism:
      Balances the use of energy among nodes to avoid exhaustion.

    - Use of TDMA for Communication:

Eliminates chances of collision and increases the efficiency of the channel.

- Local Data Collection Process:
  Decreases redundancy in communication.

LEACH Benefits

- Energy Saving:
  The use of local aggregation and minimal long-range transmission significantly reduces the energy usage.

- Load Balance:
  The rotation of cluster heads helps balance energy usage among different nodes.

- Decreased Network Traffic:
  The process of aggregation by cluster heads eliminates unnecessary data transmissions.

- Ease of Implementation:
  It is easy to implement, and there is no need to know everything about the network.

LEACH Drawbacks

Despite its benefits, LEACH has certain limitations that limit its use in current WSN systems:

- Probabilistic Cluster Heads:
  Cluster heads are chosen randomly, ignoring factors such as remaining energy and locations, making clustering less efficient.

- One-Hop Transmission to Sink:
  Cluster heads transmit data directly to the sink, making this method impractical for large-scale networks.

- Delay:
  Due to clustering, scheduling, and aggregation delays, this protocol cannot be used for real-time operations.

- Unsuitable for Large Networks:
  The efficiency of LEACH drops with an increase in the network size.

- No Event Aggregation:
  Instead of efficient event-triggered transmission, continuous data transmission is performed.

- Formation of Clusters:
  Repeated clustering in each round causes more network traffic.

Performance Considerations within the Framework

From the simulation analysis offered in this study:

  - LEACH has fair latency efficiency than direct transmission but is less effective than event aggregation-based techniques.
  - With an increase in network size (for instance, from 1000 to 5000 nodes), latency and energy dissipation significantly increase.
  - The LEACH protocol is ideal for energy-centric applications rather than latency-based ones.

Major Enhancements

- Tree Construction:
  In contrast to arbitrary clustering, this approach utilizes a hierarchical tree structure, resulting in reduced communication costs.
- Event Aggregation:
  Only relevant information is communicated, avoiding unnecessary communication overhead.
- Collision Avoidance:

Effective scheduling mechanisms prevent data transmission collisions.

- Superior Latency Management:
  Specifically designed for real-time and latency-critical operations.

LEACH paved the way for hierarchical routing in wireless sensor networks through clustering and data aggregation techniques. Although LEACH offers substantial improvements over direct transmission regarding energy efficiency, it remains inadequate in addressing latency-sensitive and extensive applications. In response to these shortcomings, the current study incorporates structured tree construction, event aggregation, and sophisticated scheduling to attain a more favorable trade-off between energy savings and latency.

1.2.2 CTP (Collection Tree Protocol)

One of the most popular routing protocols that are based on trees and have been extensively used in WSNs is known as the Collection Tree Protocol (CTP) [19, 58, 92]. In contrast to the clustering-based algorithm like LEACH, CTP builds an adaptive tree-like structure for the transmission of data from sensors to the base station. This protocol has been specifically developed to provide high levels of reliability and flexibility in changing and lossy communication scenarios.

CTP is characterized by its reliance on the link-quality routing principle and outperforms conventional routing protocols due to this distinctive feature [20, 45, 87]. Moreover, CTP constantly evaluates the current state of the network and adjusts the routes between nodes accordingly, allowing it to ensure stable communication irrespective of changes or potential issues in links or wireless connections. As a result, CTP can be considered an effective benchmark for assessing innovative methods of data transmission.

Working of CTP

The way in which CTP works can be seen as an ongoing and adaptive process that includes construction of trees, optimizing routes, and forwarding of data.

1. Tree Construction Process

- In the first phase, the sink node broadcasts its beacon message consisting of the routing information.
- Every node receiving this message evaluates the routing metric, which in case of CTP is called the Expected Transmission Count (ETX).
- This metric denotes the expected number of times a packet needs to be transmitted to deliver the message over the channel successfully.
- All nodes choose a parent with a lower ETX value, thereby guaranteeing effective transmission of messages.
- This process goes on iteratively until a tree structure is formed.

2. Route Optimization Using ETX Metric

ETX is an important routing metric used by CTP and can be calculated as follows:

$$ETX = \frac{1}{d_f \times d_r}$$

Where:

- d_f = forward delivery ratio
- d_r = reverse delivery ratio

Lower ETX values indicate better link quality and fewer retransmissions.

Each node maintains:

- Its own ETX value
- ETX values of neighboring nodes
- The best parent based on minimum cumulative ETX

3. Data Forwarding Process

- Sensors produce data packets and send them to their chosen parent node.
- The parent node will forward the packets to another parent node closer to the sink.

- This will continue until the data packets reach the sink node.

4. Dynamic Route Maintenance

The CTP protocol ensures dynamic route maintenance by:

- Routing Information Broadcasting: Broadcasted at regular intervals
- Parent Node Switching: Changes parents if the quality of link decreases
- Route Loop Detection and Repair: Routes looping in the network are identified and repaired.

5. Data Delivery Reliability Enhancements

CTP protocol uses several techniques to increase data delivery reliability:

- Link Estimation: Regularly evaluates the quality of links
- Packet Retransmission: To ensure packet delivery if there are link problems
- Packet Duplication Prevention: Prevents duplicate packet forwarding
- Dynamic Beaconing: Controls the transmission rate of beacon packets

Characteristics of CTP

- Tree-Based Routing Architecture:
  Offers a systematic approach to communicating with the sink.

- Parent Node Selection Using ETX:
  Guarantees a robust communication link.

- Self-Adaptability:
  Adapts to network dynamics like link breaks or node movement.

- Communication Over Multiple Hops:
  Facilitates data transfer in extensive networks.

- Reliability and Robustness:
  Tailored for wireless networks prone to losses.

Advantages of CTP

- High Reliability:
  The ETX-based routing mechanism ensures that data is routed along the most reliable routes.

- Flexibility:
  Can efficiently cope with varying network dynamics.

- Scalability:
  Functions well in medium to large networks.

- Efficient Multi-hop Communication:
  Prevents long-range data transfer.

Disadvantages of CTP

Although the protocol is strong, CTP has several weaknesses when considered under contemporary WSN constraints:

- High Control Traffic:
  Periodic beaconing consumes extra energy.

- Data Aggregation Absence:
  Transmits data without removing redundancies.

- Higher Latency:
  Involves multi-hop forwarding without scheduling and suffers from high latency.

- Congestion at Sink Nodes:

The vicinity of sink nodes bears heavy traffic loads.

- Inefficient Energy Utilization:
  The parent nodes closer to the sink drain more power and thus fail early.

- Non-Event-Driven Protocol:
  Constant data streaming leads to unnecessary transmission.

Observations about Performance in Context

According to simulation analysis performed in this study:

- CTP offers superior reliability compared to direct routing; however, it takes much time than an event-aggregation approach.
- Increased latency and congestion can be observed with growing network size (e.g., from 1000 to 5000 nodes) near the sink node.
- Energy expenditure is high due to constant communication and control traffic.
- CTP functions effectively in static environments, failing to meet the demands of latency-critical applications.

Important Enhancements Over CTP

- Aggregation of Event Data:
  Eliminates unnecessary data transmissions and communication overhead.

- Hierarchy-Aware Aggregation Tree Structure:
  Provides an optimized hierarchical structure to minimize hops and increase efficiency.

- Collision-Free Communication Using TDMA:
  Ensures optimal scheduling, eliminating collisions and minimizing delays.

- Load Balancing Near Sink Node:

Avoids congestion in the proximity of the sink node due to systematic communication.

- Optimized Latency:
  Tailored to real-time and latency-sensitive application scenarios.

CTP is a strong and dependable tree-based routing protocol, capable of providing efficient multi-hop data collection services in WSNs. CTP's key advantages include its adaptive routing and intelligent decision making based on link quality. Yet, CTP does not provide any support for aggregation, scheduling, or latency optimization. The suggested research leverages the benefits of CTP, while compensating for its drawbacks through event aggregation, hierarchical tree optimization, and intelligent scheduling mechanisms.

1.3 FTSP (Flooding Time Synchronization Protocol)

FTSP stands for Flooding Time Synchronization Protocol, a common protocol utilized in WSNs aimed at providing time synchronization services for the sake of distributed sensors that form a wireless sensor network. When multiple nodes in a WSN work simultaneously in order to sense, compute, and transmit information, it is vital that there should be some kind of uniform understanding of time within the network.

While routing protocols, like LEACH and CTP, are responsible for sending data from one node to another, FTSP performs an entirely different function. While routing protocols are higher layer protocols that perform actual data transmission or routing, time synchronization is a fundamental feature without which other protocols cannot operate. As regards this study, time synchronization is vital for TDMA-based scheduling and synchronization in data aggregation.

Working Mechanism of FTSP

FTSP works on a flood-based method, where information about synchronization is periodically sent all over the network so as to maintain a global time.

1. **Selection of a Reference Node**

   A reference node (sink node) is chosen in the network.

   This node serves as a global time source and performs synchronization.

2. **Time Synchronization Message Broadcasting**

   The reference node periodically sends out synchronization messages, which contain timestamp information.

   This includes:

   - Timestamp of the local time at the sender
   - Sequence number
   - Transmission time of the message

3. **Timestamping Scheme**

   FTSP applies MAC-level timestamping, thus improving time synchronization accuracy due to low errors introduced by delays.

   Time stamps are taken at the exact moment the message is sent or received, minimizing errors introduced by software processes.

4. **Clock Adjustment at Receiving Nodes**

   At receiving nodes:

   - The reception time of the message is noted
   - Compared against the timestamp of the sender
   - Local clock adjusted based on the comparison
   - Multiple such messages undergo linear regression analysis for:
   - Clock drift estimation
   - Improved synchronization accuracy

5. **Multi-hop Synchronization Using Flooding**

   Messages are repeatedly broadcasted by nodes receiving the synchronization message to other neighboring nodes.

Key Characteristics of FTSP

- Precise Synchronization:

  Microsecond synchronization accuracy using MAC-layer timestamping.

- Flooding-Based Synchronization:
  Makes sure that time information propagates to all nodes.

- Clock Compensation Mechanism:
  Compensation for clock drift by use of regression techniques.

- Resilience to Network Changes:
  Can accommodate node removal and topological changes.

Benefits of FTSP

- Precise Synchronization:
  Time synchronization is essential for effective operation such as scheduling and data fusion.

- Suitability for TDMA-based Communication:
  Enables time slot allocation, minimizing collisions.

- Network Coordination:
  The nodes synchronize their behavior, becoming more efficient.

- Scalable Method of Synchronization:
  Efficient operation in multi-hop networks and other scenarios.

Drawbacks of FTSP

In spite of numerous benefits, there are also some drawbacks of FTSP:

- Increased Communication Load:
  Flooding of synchronization messages creates unnecessary communication load.

- Energy Consumption:
  Increases energy costs through broadcasting of messages.

- Partial Approach to Networking:
  Only deals with time synchronization; lacks other features.

- Possible Delay Propagation:
  In multi-hop case delays tend to propagate.

- Difficult to Implement:
  Requires precise timing and clock compensation mechanisms.

Observation Concerning the Performance in the Context

In connection to this research:

- Improves coordination among the nodes; therefore increasing efficiency of scheduling.
- But energy costs increase through regular broadcasting of messages.
- Does not improve performance unless used in conjunction with proper scheduling.
- Dependent on synchronization intervals and size of the network.

The FTSP protocol plays a vital role in providing time synchronization in WSNs, and without it, communication and scheduling cannot take place. Although the FTSP protocol is accurate in terms of synchronization and allows for systematic communication, it fails to provide any solutions to issues related to routing, aggregation, and latency minimization. The current research proposes to build on the idea of time synchronization by incorporating scheduling, aggregation, and routing into its framework.

1.4 Direct Transmission Approach

The Direct Transmission is one of the simplest forms of communication strategy in WSNs, which is characterized by each individual node transmitting its data straight to the base station without the involvement of any intermediate nodes or routing protocols. In most cases, the technique is used as the reference point for assessing the efficacy of other communication strategies.

Under the strategy, each individual node transmits the collected information directly to the base station irrespective of the distance separating them. While the strategy significantly simplifies the communication process, it poses major drawbacks such as inefficiency, energy consumption, and poor scalability among others. Within the context of this study, Direct Transmission can be used as a benchmarking tool for illustrating the advantages of the proposed rapid data transmission protocol.

Direct Transmission Working Principle

The Direct Transmission scheme is very simple, and there is no hierarchy, coordination, or any other type of structure involved.

1. Independent Data Sensing
   Every sensor node collects data from the environment independently.
   There is no cooperation or interaction between any nodes.

2. Single-Hop Data Transmission to the Sink Node
   Each node communicates data directly to the sink node.
   Generally, it is a single-hop process independent of distance.

3. No Data Aggregation
   It involves transmitting raw data without compression.
   Thus, a lot of transmissions will be required in the network.

4. No Transmission Scheduling
   Any time transmission can take place without coordination between nodes.
   Thus, it is likely to lead to many collisions in the communication channel.

Main Features of the Scheme

- Flat Network Architecture:
  There is no hierarchy in the architecture.

- Single-Hop Transmission:

All nodes communicate with the sink directly.

- No Data Aggregation:
  It involves no data processing.

- Transmission without Coordination:
  There is no scheduling of transmissions.

Benefits of Direct Transmission

Despite its simplicity, Direct Transmission has some merits, particularly for small applications:

- Simple Implementation:
  It requires no complex algorithms to implement.

- No Routing Issues:
  It does not require routing tables or routing structures.

- Quick Data Transmission:
  It is faster than aggregation-based schemes.

- Minimal Processing Required:
  It is good for low-cost sensor nodes.

- Suitable for Short-Distance Applications:
  It works efficiently for small-scale WSNs.

Drawbacks of Direct Transmission

While seemingly straightforward, there are various disadvantages of Direct Transmission, which make it unsuitable for application within practical WSNs:

1. **High Energy Consumption**
   The farther a node is from the sink, the higher the transmission power requirement.
   Results in quick battery drainage.

2. **Inefficiency**
   Efficiency is compromised when there is an increase in the number of nodes.
   Cannot be used in large networks.

3. **Packet Collisions**
   Collisions occur as different nodes send information at once.

4. **Network Congestion**
   Congestion results due to high activity around the sink node.

5. **High Latency**
   Collisions result in delayed delivery of packets.
   Cannot be used in applications requiring low latency.

6. **Unequal Energy Consumption**
   Increased consumption of energy by distant nodes.
   Can lead to failure of some nodes.

The Direct Transmission scheme offers a straight-forward and efficient way of communicating data in WSNs. Nevertheless, due to the absence of data aggregation, routing, and scheduling, this technique has some shortcomings such as high energy usage, limited scalability, and high delays. Despite its appropriateness for small networks, this technique cannot perform well in large-scale and real-time WSN applications.

In this study, the drawbacks of the Direct Transmission scheme have been addressed by developing a hybrid model that combines the use of tree-based routing, event aggregation, and smart scheduling techniques.

1.5 Event Aggregation-Based Protocol

The newly developed Event Aggregation-Based Protocol would form the central feature of this project as an attempt to overcome the major shortcomings associated with existing WSN communication methods. While other communication solutions tend to give priority to one of two criteria – power saving or minimizing time delay – the suggested protocol takes into consideration both these criteria.

The need for moving from continuous data transfer to event-based information exchange, whereby all insignificant data will be filtered out and only significant information will be transferred through the WSN. To accomplish this objective, this project uses the combination of several components, including tree generation, hierarchical aggregation, and efficient scheduling.

Thus, transferring raw sensor readings to a base station without filtering them creates unnecessary energy usage, results in network congestion, and increases chances of collision in practical scenarios, such as gas leak monitoring or indoor air pollution monitoring. By adopting this protocol, the sensor nodes are able to process all the received data locally and then transfer only necessary information.

Principle of Operation of the Proposed Protocol

The operation of the proposed protocol is done via a number of stages, which make it effective in terms of communication and ensure the minimization of redundancy and delays.

1. **Generation of Events at Sensor Nodes**
   Sensor nodes monitor the environmental factors continuously.
   As opposed to data, events are generated on-site by analyzing the data sensed.
   Data is transformed into events like:
   - "Gas levels have exceeded threshold"
   - "Air quality has turned unhealthy"

   Only relevant events are communicated to the next layer of the hierarchy.

2. **Dominator-Dominatee Hierarchy**
   - The entire system operates in a hierarchy that includes:

- Dominators (nodes for aggregating data)
- Dominatees (sensor nodes)
- Every dominatee communicates to the nearest dominator only.
- It helps in minimizing transmission distances and network balance.

3. **Greedy Aggregation Tree Formation**
    - Tree-based formation with a greedy algorithm entails:
    - Connecting to the nearest possible parent node.
    - A hierarchy that ensures minimal hops and efficient routing.
    - Eliminating redundant connections in order to create an optimal aggregation tree.
    - Routing is done from one level to another in the hierarchy.

4. **Hierarchical Data and Event Aggregation**
    - Every layer of the hierarchy involves:
    - Aggregate data sent from a number of dominatees at once.
    - Aggregation function f(A) transforms multiple inputs into an output.
    - Event aggregation eliminates the unnecessary data.
    - Significantly minimized:
        - Number of transmissions
        - Network congestion
        - Energy consumption

5. **Distributed Scheduling Using TDMA**

    Nodes receive time slots through a distributed scheduling algorithm.

    Transmission by nodes takes place only during their respective time slots.

    This leads to:

    - Transmission without collision
    - Optimal use of channels
    - Minimum number of retries

6. **Data Transmission to Sink**

    Data is aggregated and then forwarded to the root, which is at the topological center.

The root node sends the final data packet to the sink using the shortest path.

Key Characteristics of the Proposed Protocol

- Event-Driven Communication:
  Avoids unnecessary transmission and transmits only useful data.

- Hierarchical Network Architecture:
  Dominator-dominated architecture provides good scalability.

- Greedy Tree Algorithm:
  Provision of efficient routing with low overhead.

- Built-In Data Aggregation:
  Involves both data aggregation and event aggregation.

- Scheduling Through TDMA Technique:
  Provides collision-free and energy-efficient communication.

- Hybrid Approach:
  Centralized tree construction with distributed scheduling.

Strengths of the Proposed Protocol

1. **High Energy Efficiency**
   Decrease in unnecessary transmission.
   Data aggregation makes the transmission process efficient.
   The transmission energy load is shared among nodes.

2. **Fast Communication**
   Event-driven transmission ensures minimum latency in communication.
   Efficient scheduling avoids congestion and re-transmission.
   Ideal for real-time application systems.

3. **Minimal Packets Collision**

   Collision-free communication is possible using TDMA.

   Only one node can transmit at once.

4. **High Scalability**

   High scalability provided by hierarchical architecture.

   Operates efficiently regardless of node density.

5. **Minimal Network Congestion**

   Aggregation process limits packet size.

   Event-driven transmission prevents network congestion.

6. **Even Network Distribution**

   Tree-based communication is effective in load distribution.

   No early battery exhaustion of individual nodes.

Performance Improvements

Performance Gains

The new approach shows marked gains compared to existing methods:

- Latency Improvement:

  A decrease by about 50%–60% compared to direct communication and standard aggregation techniques.

- Energy Savings:

  Consume less energy because of fewer transmission events and efficient routing.

- Scalability Performance:

  Remains consistent with respect to network size, including:

- Small networks (50 devices)

  Moderate networks (150–1500 devices)

Large-scale networks (>5000 devices)

- Collisions Minimization:
  Approaches zero since all communications are scheduled.

Practical Relevance in This Research

The efficiency of the protocol will be verified by means of:

- Simulation (Castalia & NS2):
  Verifying efficiency in terms of energy, latency and scalability.

- Real-Time Application:
  Gas sensor (MQ7) and NodeMCU application.
  Showing how the event-based transmission works.

These two forms of verification ensure that the suggested protocol is efficient from both theoretical and practical perspectives.

Event Aggregation-Based Protocol, presented in this research paper, presents an efficient tool for data transmission in the context of Wireless Sensor Networks. The suggested protocol combines several aspects including tree-based routing, hierarchical event aggregation and scheduling to solve all possible problems associated with energy costs, latency and scalability.

As compared to traditional protocols, the suggested solution places particular emphasis on the event-driven transmission, thus eliminating unnecessary messages. Consequently, the suggested protocol is perfectly applicable for modern applications in the field of Wireless Sensor Networks.

1.6 Background and Motivation

Wireless Sensor Networks (WSNs) have emerged as an important enabling technology for many of today's data-dependent applications like environmental monitoring, health care systems, industrial control, military operations, and smart city applications. The WSN comprises numerous sensor nodes that work together to monitor, analyze, and transmit the data to the main sink node in the network. Given the capability of the WSN to function under harsh conditions, they are very useful in real-time systems where monitoring and decision making are required.

However, WSNs are subject to a number of shortcomings. Sensor nodes in WSNs usually have low processing power and run on batteries while working on a very narrow communication range. Thus, ensuring the efficient transmission of the data is one of the major concerns in designing wireless sensor networks. Energy consumption has traditionally been the most common focus area of WSNs researchers to increase system lifetime.

However, the requirements of WSNs have evolved due to the introduction of new applications like real-time monitoring, disaster management, and IoT-based applications. Apart from energy efficiency, low latency is another requirement, which means that the data has to be transmitted within a short period without compromising on reliability. If not done so, the results can be disastrous in scenarios like gas leakage detection or health monitoring.

Convergecast is one of the most prevalent communication paradigms employed in WSNs. It involves collecting data from different nodes in a network using multi-hop communication before being sent to a sink node. Although it offers organized data collection, it has some challenges, including packet collisions, unnecessary transmission, network congestion, and high latency. Some of the techniques that have been employed to address these challenges include data aggregation, event-based computing, and scheduling schemes. However, most solutions available today emphasize enhancing either the energy efficiency or latency of a WSN. The need to enhance both aspects has led to the introduction of frameworks that integrate tree-based routing and aggregation algorithms with effective scheduling.

1.7 Technical Challenges

To design a data transmission system efficiently in WSNs, one needs to solve several technical problems. The reasons for these problems lie in the constraints imposed by the sensors, the network dynamics, and the growing need for real-time data transmission. Understanding the problem at hand is a prerequisite for creating an effective solution.

- Energy Efficiency:

  Energy efficiency remains one of the most important problems in WSNs. The sensor nodes have batteries of limited capacity and are deployed in hard-to-reach areas where changing the battery or charging it becomes unfeasible. Communication consumes much energy from the sensor node especially during data transmission. It means that it is crucial to develop methods of data transmission that will require minimum energy to ensure communication. Energy inefficient use can result in premature depletion of batteries and affect the lifetime and performance of WSN.

- Minimization of Delay:

  Now that applications like real-time health care, disaster response, and automated industry have come into focus, minimizing transmission delay is also crucial. Data should reach the sink node within a certain time limit to make decisions in time. On the other hand, decreasing delay results in increased frequency of data transmission and decreased buffering of data, thereby increasing the energy consumption. It is a complex task to minimize latency and maximize energy efficiency at the same time.

- Packet Collisions and Interferences:

  In WSNs, the communication takes place using a common wireless channel. Whenever more than one node tries to transmit information at the same time, there are chances of packet collision, leading to information loss and causing re-transmission. This will in turn increase the amount of energy consumed along with increasing the delay. The effect of interference by other nodes or other signals is also a factor that can affect the communication process in WSNs.

- Network Congestion:

  Network congestion is one more challenge in WSNs, particularly when the network has many densely packed sensor nodes that try to communicate through a few communication links. As a result, congestion causes an increase in delays, dropping of data packets, and lengthy queues, thus affecting the overall efficiency of the network. Hence, the traffic congestion must be controlled for better performance of the network.

- Scheduling Inefficiencies:

  Proper scheduling plays an important role in ensuring that data transfer from sensor nodes is effectively coordinated. Poor scheduling techniques may result in problems like collisions, wasted slots, and delays. Many traditional scheduling algorithms rely on information available in the network at the moment (myopic scheduling). It is necessary to develop effective scheduling algorithms that make scheduling decisions based on both current and future network states.

- Non-scalable Methods:

  While many existing solutions are highly effective in small and medium-sized networks, they do not scale well when deployed in large networks. This may lead to performance losses, thus making such solutions inefficient. For instance, non-scalable solutions suffer from challenges associated with scaling, such as routing, communication, and interference. Consequently, scalability is an important aspect in designing WSN algorithms.

- Dynamic Environment:

  Due to the dynamic nature of many applications involving WSNs, it is important to implement systems that will enable adjustments to be made in case of changes in network dynamics. Changes may come as a result of several conditions like mobility of nodes, interference in the environment, and communication links among others. Without such mechanisms, the effectiveness and reliability of the network will decrease significantly.

  - Fault Tolerance

    It is necessary for the WSN to be able to tolerate any faults for effective communication. Some of the possible faults within a WSN include node failure, communication failure, and even sink failure. The faults may arise from a number of reasons such as lack of energy or damage to the hardware. Ensuring efficient communication in such scenarios is another challenge that must be solved. Several methods like retransmission and link quality assessment techniques (RSSI and LQI) have been used.

1.8 Research Objectives

The main goal of this study is to propose and design a fast data transfer system for Wireless Sensor Networks with low latency and energy consumption.
The goals include:

- Designing a strategy for generating optimal trees for effective data routing
- Designing data aggregation strategies to eliminate unnecessary data transfer
- Designing event-based data aggregation for efficient data presentation
- Designing intelligent scheduling algorithms, including non-myopic schemes
- Minimizing packet collision and minimizing communication cost
- Improving scalability and adaptability of the network
- Implementing fault-tolerant communication strategies
- Validating the proposed design through simulation and real-time deployment

1.9 Thesis Outline

The thesis is organized into five chapters, each focusing on a specific aspect of the research:

Chapter 1: Introduction
This chapter presents the background, motivation, technical challenges, research objectives, contributions, and overall structure of the thesis.

Chapter 2: Literature Review
This chapter provides a comprehensive review of existing research on convergecast communication, data aggregation, scheduling policies, and tree-based routing in WSNs.

Chapter 3: Proposed Architecture
This chapter describes the proposed framework, including tree generation, aggregation mechanisms, scheduling strategies, and algorithm design.

Chapter 4: Result Analysis
This chapter presents simulation results and performance evaluation, comparing the proposed approach with existing protocols.

Chapter 5: Conclusion and Future Work

This chapter summarizes the research findings and discusses potential directions for future work.

CHAPTER – 2

Literature Review

The use of Wireless Sensor Networks (WSN) technology has become an indispensable component for the creation of many data-based systems due to the capability provided by this kind of networks in terms of effective data collection, monitoring, and control. Such applications vary from environment monitoring through healthcare systems to military systems and industry, as well as other sectors, like smart city management. The need to obtain up-to-date information and make decisions based on it contributes to increased popularity of WSNs.

A Wireless Sensor Network consists of numerous sensor nodes located throughout the area. They are installed in order to acquire information about the surrounding environment and send this information to the so-called sink node or base station. This way, the main tasks of such sensor nodes can be described as follows: sensing some environmental parameter, processing this information, and communicating it to the outside world [1, 50]. The function of the base station is to serve as a link between the internal part of the sensor network and the external systems using the information received from WSN [30, 56].

Because of the large scale and distribution of WSNs, communication between sensor nodes becomes very essential. There are several methods of communication that have been proposed in literature [22, 47, 73]. One such paradigm which has become increasingly popular in the literature for the purpose of data collection in WSNs is convergecast communication. Convergecast is the process by which the data collected from various sensor nodes is routed towards a central sink node. This usually occurs in multi-hop communication channels [56, 88, 47]. The intermediate nodes can be used not only for routing purposes but also for aggregation and filtering.

But developing efficient convergecast communication protocols in WSNs is extremely difficult because of the restrictions imposed by WSNs. The sensor nodes are powered by batteries and therefore have limited power supply. They have limited memory space and computational capability [28, 74, 76]. Moreover, they have limited bandwidth available for communication over wireless channels. All these factors make the development of efficient convergecast protocols in WSNs very challenging.

Numerous studies have been carried out to solve the above problems and optimize convergecast communications. The techniques suggested by researchers were mainly focused on solving the issues related to the performance criteria. Energy-efficiency, transmission delays, reliability, and scalability are among the most important aspects of convergecast communication systems which have to be optimized to provide the highest possible performance. Some techniques include data aggregation aimed at minimizing redundant transmission and energy consumption, and scheduling schemes aimed at decreasing transmission conflicts and delays [29, 58, 47].

However, despite the advances made, it is still very difficult to ensure balanced optimization of all the performance criteria. The majority of existing solutions to the mentioned problems consider only one aspect of convergecast communications, while ignoring others, thus creating new issues for the further functioning of the system. In order to achieve more efficient and flexible communication in WSN, there is a need to use an integrated approach and take into account all relevant issues related to the process of information transfer [31, 54, 44]]. The review of the current techniques and approaches for convergecast communication will be provided in the following subsections.

2.1 Convergecast Problem and Challenges

Convergecast addresses the issue of the efficient gathering of data generated by different nodes and sending it to a central sink node while keeping the costs low and improving the network performance as much as possible. The main concern during the initial years of studying WSNs has been energy efficiency due to the use of batteries as the power source for sensor nodes. Hence, solutions were developed to minimize the number of communications, optimize the route used, and increase the network lifetime [1].

But with the quick development of applications like disaster management systems, health monitoring applications, automation systems, and environmental sensors, the demands for WSNs have changed dramatically. In addition to energy efficiency, latency became an equally important factor, since in many cases timely information exchange is vital to make the right decisions.

Among some of the most pressing problems in convergecast communication includes packet collision; this occurs where several sensor nodes try to send their packets at once through a wireless communication medium. Packet collisions result in lost packets and increased number of re-transmissions, thereby increasing energy utilization and delays in transmission [53, 75, 80]. Apart from collisions, problems like channel contentions, interference and unnecessary re-transmissions also limit the effectiveness of networks.

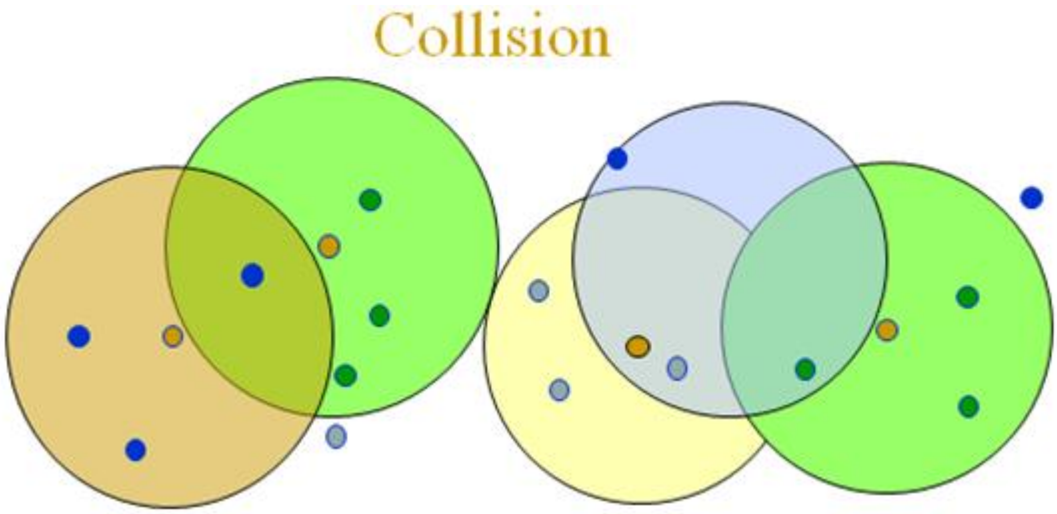


Figure 2.1: Collision in the Convergecast Problem [1]

Additionally, as the network grows in size, the problem of controlling and coordinating communications within the network becomes more difficult; hence, the congestion levels increase [100]. Thus, in current investigations into the problem of convergecast communication, the major objective is to strike a balance between energy utilization and delays for enhanced network performance. Finding solutions to this conflict presents one of the greatest challenges faced by modern researchers developing Wireless Sensor Networks.

2.2 Distributed Convergecast Algorithms

In order to overcome issues of scalability and dynamically varying network environments, distributed algorithms for convergecast have been designed as alternatives to centralized solutions. In such techniques, each sensor node decides individually about its own transmission protocol using local information; therefore, there is no requirement of any global information regarding the network. The flexibility associated with distributed techniques makes them suitable for large WSNs [2, 4].

The general process followed by a distributed convergecast protocol works as follows:

- The transmission range of individual nodes is set in such a way that it facilitates communication with the closest neighboring node.
- Messages are sent with a specific probability p, which reduces the possibility of collisions due to simultaneous transmission.
- After successful message transmission without collision, the node goes into a sleep mode, and hence saving energy becomes possible.
- In case of collision, messages are aggregated to save on energy.

These approaches work in conjunction to make the system more efficient in terms of energy usage.

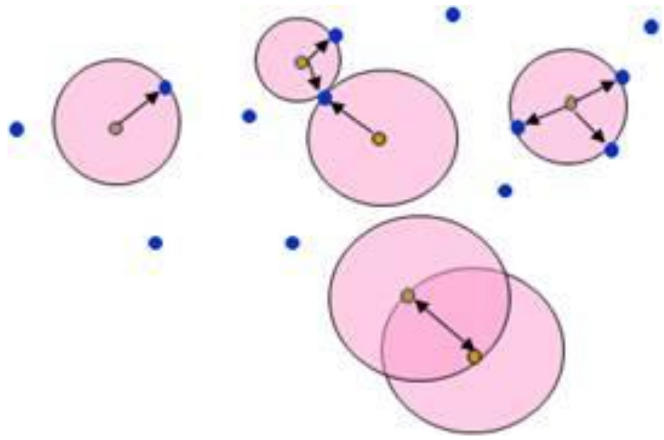


Figure 2.2 Distributed Convergecast Algorithm [4]

In addition to that, distributed algorithms increase network reliability, since failure of one node doesn’t affect system performance. Nonetheless, there are some drawbacks associated with distributed convergecast algorithms. Since the lack of centralized control leads to decentralized decision-making, the choices that each node makes may not necessarily be the most efficient from the overall network's standpoint. Consequently, this might increase the latency of data transmission, particularly when several nodes are trying to access limited network resources. In addition, the use of probabilistic transmissions may affect the consistency of data flow.

2.3 Data Aggregation in WSNs

One of the popular methods used to improve the communication process of convergecast in Wireless Sensor Networks is data aggregation. The essence of data aggregation lies in merging several packets of data originating from different sensors in the intermediate nodes, followed by sending the aggregated data to the sink node through a single packet. Data aggregation is therefore highly significant in the reduction of communication overhead due to less number of transmissions [5].

Some benefits associated with the use of data aggregation method include:

Packet collision reduction due to limited simultaneous transmissions

Reduction of communication overhead through reduction of redundancy of data transmission

Energy saving, which may amount to as high as 70% in some networks

Furthermore, besides data aggregation, in-network filtering may also be performed to filter out redundant and unnecessary data prior to transmission.

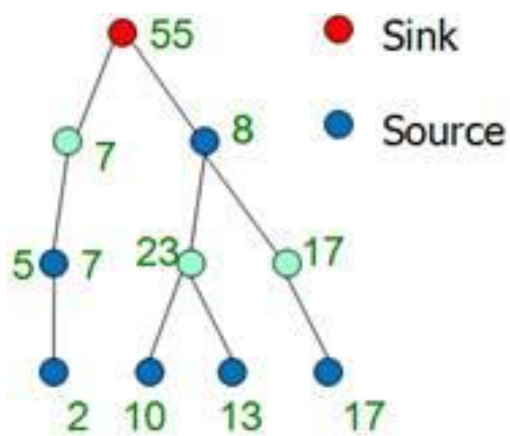


Figure 2.3 Data Aggregation Convergecast [5]

However, although there are numerous advantages associated with data aggregation, there is always a fundamental tradeoff between energy savings and delay due to the aggregation process. Before the intermediate node is able to combine and send out the data, it must first gather the information from different child nodes. The process will take some time and results in delays during the aggregation process. With larger networks, delays may cause additional end-to-end delays.

It can thus be seen that although data aggregation offers many advantages in terms of saving energy and reducing costs of communication, it should be done efficiently to avoid any delays.

2.4 Event-Based Aggregation

The method of Event Based Aggregation can be described as a more sophisticated enhancement to the usual aggregation techniques used [73, 84, 72]. With this technique, data sensed by the node is not sent as raw data but is processed first and transformed into high-level semantics, for example, “temperature exceeds threshold” or “motion detected.” This process of transforming raw data into higher level information is highly efficient for the purpose of communicating data.

An important benefit that event based aggregation offers is data abstraction. Data abstraction makes interpretation much easier as only meaningful pieces of information are communicated and not the redundant ones. This technique makes the whole process of communicating much more efficient in terms of energy as well because now the communication channel is free from all unnecessary data being transferred [34, 49, 53].

Moreover, the use of event-based aggregation facilitates the application of such methods both to energy-limited and latency-sensitive applications since only required information will be transmitted, thus saving bandwidth, minimizing latency, and accelerating the data transfer process. In addition, this approach provides the opportunity for the development of event-driven aggregation trees whose routing and aggregation processes are dependent on events, rather than constant data streams.

2.5 Delay Bounded Event Aggregation (DBEA)

In order to deal with the delays created by conventional approaches, the concept of Delay Bounded Event Aggregation (DBEA) was introduced [43, 55]. The Delay Bounded Event Aggregation technology provides a predetermined time window in which data aggregation should take place, thereby guaranteeing the completion of the transmission within an appropriate delay bound [4, 6].

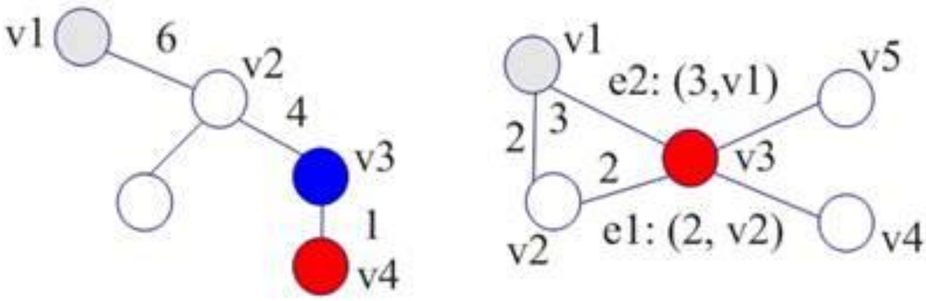


Figure 2.4 Delay Bounded Event Aggregation Algorithm [4]

The properties of DBEA include:

- Transmission within a given delay bound
- Balancing energy savings and latency issues
- Saving about 35% of energy compared to non-optimized cases

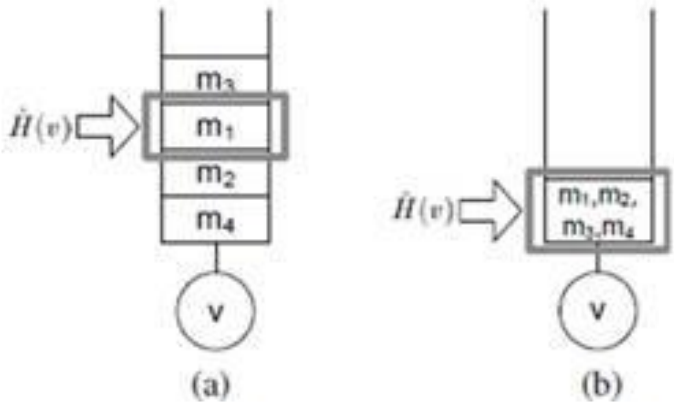


Figure 2.5 Delay Performance of Scheduling with Data Aggregation [6]

Unlike the conventional approach to aggregation, with DBEA it becomes possible to aggregate data partially instead of not aggregating at all when the completion of the process of aggregation is not feasible within the provided time window.

2.6 Influence of Aggregation on Performance in Terms of Delay

The effects of data aggregation on the performance of wireless networks, especially in terms of delay, have been widely studied in the literature. Data aggregation has a great influence on the total delay in convergecast communication.

Without In-Network Aggregation:

In the case of no aggregation, every node sends its data separately, resulting in many concurrent transmissions. Hence, channel contention increases, as does the likelihood of collisions. Retransmissions occur more often, leading to increased overall delay and power consumption.

$$\sum_{m \in \hat{V}} D_m \geq O(n^2)$$

With In-Network Aggregation:

On the other hand, when aggregation is performed, intermediate nodes aggregate the data received from several sources and send one aggregated packet. Thus, fewer transmissions take place, and channel contention is minimized. The total delay is decreased.

$$\sum_{m \in \hat{V}} D_m \leq O(n \log n)$$

This implies that aggregation has a considerable effect on the performance of wireless networks, especially in densely packed WSNs, where overhead becomes an issue. However, care should be taken not to introduce any unnecessary delay while aggregating the data.

2.7 Scheduling Policies for Efficient Convergecast

The implementation of effective scheduling policies can significantly help in coordinating the exchange of information between sensor nodes and preventing potential conflicts in data transfer operations. Proper scheduling ensures that delays, packet collisions, and loss of information are kept at an absolute minimum.

Scheduling methodologies are primarily divided into two major types:

Myopic Scheduling Policies

These scheduling policies operate based on the immediate status of the network only. Myopic scheduling techniques tend to be quite straightforward and inexpensive from a computational standpoint.

Maximum Weight Matching (MWM): Concentrates on reducing incremental delays and scheduling essential transmissions
Maximum Size Matching (MSM): Seeks to enhance the size of concurrent transmissions
Greedy Maximal Matching (GMM): Employs local optimization for scheduling transmissions

Although myopic scheduling techniques are convenient to employ, they might sometimes fail to provide optimal solutions.

Scheduling Policies that are Non-Myopic

Non-myopic scheduling policies take into account the present state and the future state of the network, leading to decisions that are made with better information.

Non-Myopic Max-Weight Matching (NM-MWM): An extension to MWM which takes future network states into consideration
NM-MWM with analysis (NM-MWM+A): Improves on NM-MWM by minimizing future delays
Non-Myopic Graph-based Maximal Matching (NM-GMM): Improved version of GMM

These techniques offer improved delay results and effective utilization of resources but have higher computational requirements.

2.8 Tree-Based Routing Structures for Data Aggregation

Tree-based routing structures are commonly employed for effective communication in WSNs. They provide hierarchical routing paths from the source to the destination, thus making data aggregation and transmission easier.

The following are some of the commonly used tree structures:

Shortest Path Tree (SPT): It ensures minimum transmission path and delay.
Collection Tree Protocol (CTP): It is popularly adopted in practical WSN implementation.
Minimum Interference Tree (MIT): It helps in minimizing interference among various nodes.
Bounded Degree Minimum Radius Spanning Tree (BDMRST): It helps in balancing coverage and connectivity.
Degree Constrained Tree (DCT): It improves scalability.

2.9 Centralized Data Aggregation and Scheduling

The centralized methods leverage the global information of the network for communication optimization. The centralized method usually involves the following procedure:

Step 1: Aggregation of data from the dominatee nodes to dominators via the greedy algorithm
Step 2: Connection of disconnected nodes
Step 3: Formation of the hierarchical tree (leaves, competitor, time slots)
Step 4: Transmission of data in a hierarchical fashion from lower to upper levels to sink node

The performance analysis indicates that:

No aggregation = high latency

Aggregation = low delay

Latency constraints:

Upper Bound $= 16R + \Delta - 14$

Lower Bound $= 4R + \Delta - 3$

where R is the radius of the network.

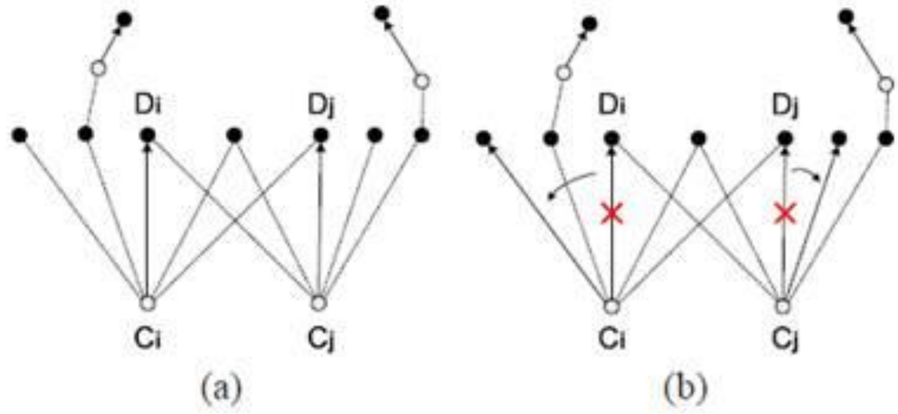


Figure 2.6 Greedy aggregation of data from dominatee nodes to dominators

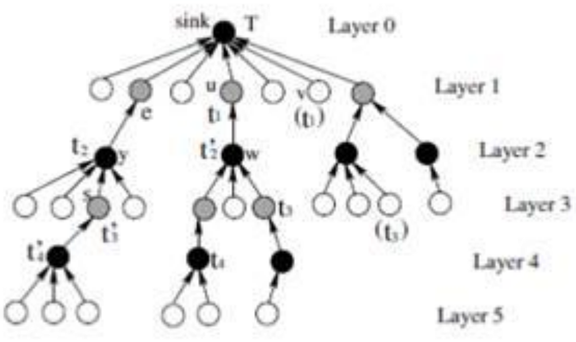


Figure 2.7 Reconnection of unlinked nodes to ensure connectivity.

2.10 Simulation Tools for Performance Evaluation

The assessment of the algorithms and communication protocols suggested for use in Wireless Sensor Networks (WSNs) calls for an extensive and regulated testing process. Real-life deployments of WSNs being costly, time-consuming, and problematic due to unpredictable environmental factors, simulation programs are very important in assessing the performance of the systems before their actual deployment.

Simulation programs facilitate the modeling of the networks and testing of the systems for their performance under various conditions and the efficiency of different techniques within a controlled environment. The simulations help in evaluating important performance parameters such as latency, energy consumption, throughput, scalability, reliability, packet delivery rate, and network lifetime.

Some of the popular simulation programs used in WSNs are:

NS (Network Simulator):

NS is a widely employed general-purpose simulation tool used for network protocols and communication schemes. The flexibility and capability of simulating layers of network make it suitable for routing and scheduling algorithms' performance evaluation.

TOSSIM:

TOSSIM is an event-driven simulator which is specially developed for TinyOs based sensor networks. It provides very accurate simulations for application level purposes due to its capability to simulate the real behavior of sensor nodes.

SensorSim:

SensorSim is a simulator which extends the capabilities of NS by adding the sensor networks related features, like sensing model and energy consumption calculation. It can be considered to provide more accurate modeling of the behavior of WSN.

Atemu:

It is a simulator that can be used to emulate hardware components of sensor nodes. Atemu gives an opportunity to research on embedded systems as well as their interaction with hardware.

Avrora:

It is a cycle-accurate simulator especially dedicated to embedded systems. Avrora allows a thorough investigation of energy consumption and program execution at the processor level.

Castalia:

It is a simulator especially made for WSNs. This simulator provides realistic modeling of wireless channel, radio communications and sensors.

The simulation is essential for verification of the proposed framework through the following means:

- Testing for varying sizes and densities of networks
- Evaluating the performance under different environmental settings
- Comparing with the established protocols and methodologies
- Saving the cost and time spent on implementation
- Acquiring understanding regarding system performance before actual deployment

With such approaches, scientists will be able to prove the efficiency and effectiveness of the proposed algorithms.

2.10.1 Small-Scale Network (16 Nodes, 60×60 m²)

This situation describes the implementation of a low-density and small-sized application with 16 sensor nodes spread over a smaller region of 60×60 m². This type of setup is generally employed in the process of validating the algorithm.

The following are the key aspects emphasized in this case:

- Energy expenditure by individual sensor nodes

- Efficiency of the communication process
- Transmission success rate
- Validation of the aggregation and scheduling technique

As the size of the network is quite limited, any problem related to congestion and interference can be ignored in this context.

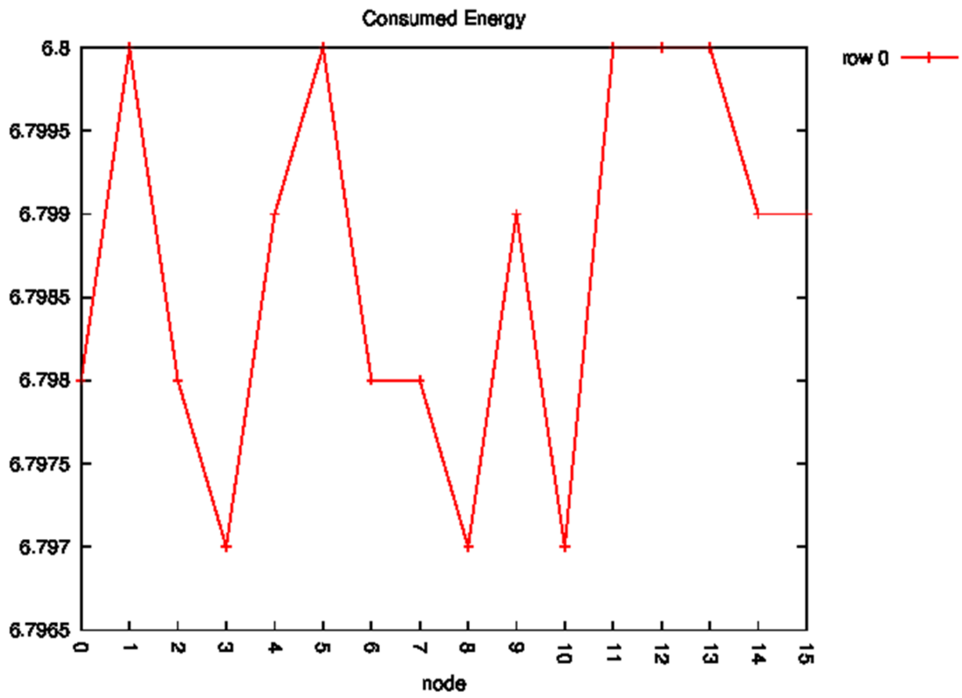


Figure 2.8 Simulation Result of 16 nodes in 60x60 meters.

2.10.2 Large Scale Network (150 Nodes, 1500 × 1500 m²)

This is another case that indicates a dense and large-scale network. It involves 150 sensor nodes deployed over a large area measuring 1500 × 1500 m². The purpose of this setting is to test the scalability and reliability of the proposed solution in a heavily loaded network.

Some of the issues to be analyzed in this network include:

- Scalability of the network
- Effect of node density on communication efficiency
- Network congestion and collision resolution

- Delay performance in high traffic environment
- Energy consumption in large scale networks

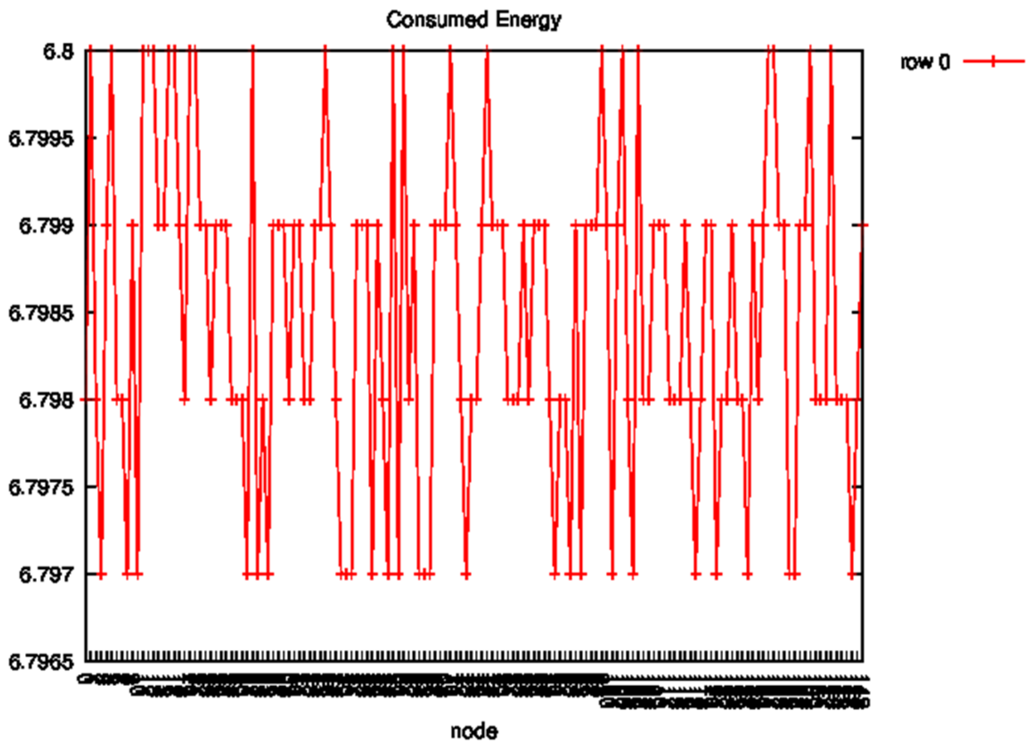


Figure 2.9 Simulation Result of 150 nodes in 1500x1500 meters

Since there are many nodes, the problem areas will include interference, packet collisions, and delays in communication.

2.10.3 Medium-Sized Network (50 Nodes, 100 × 100 m²)

The medium-scaled network case study represents a realistic balance between the easy-to-manage small-scaled case and the complex large-scaled scenario. In this case study, we have 50 sensor nodes operating in an environment covering an area of 100 × 100 m².

The case study will enable us to investigate the following issues:

- Energy consumption vs. transmission delays
- Efficiency of data aggregation and scheduling mechanisms

- Average network traffic and communication costs
- Stability and reliability of the system

A medium-scaled case study presents a practical environment that resembles real-world situations.

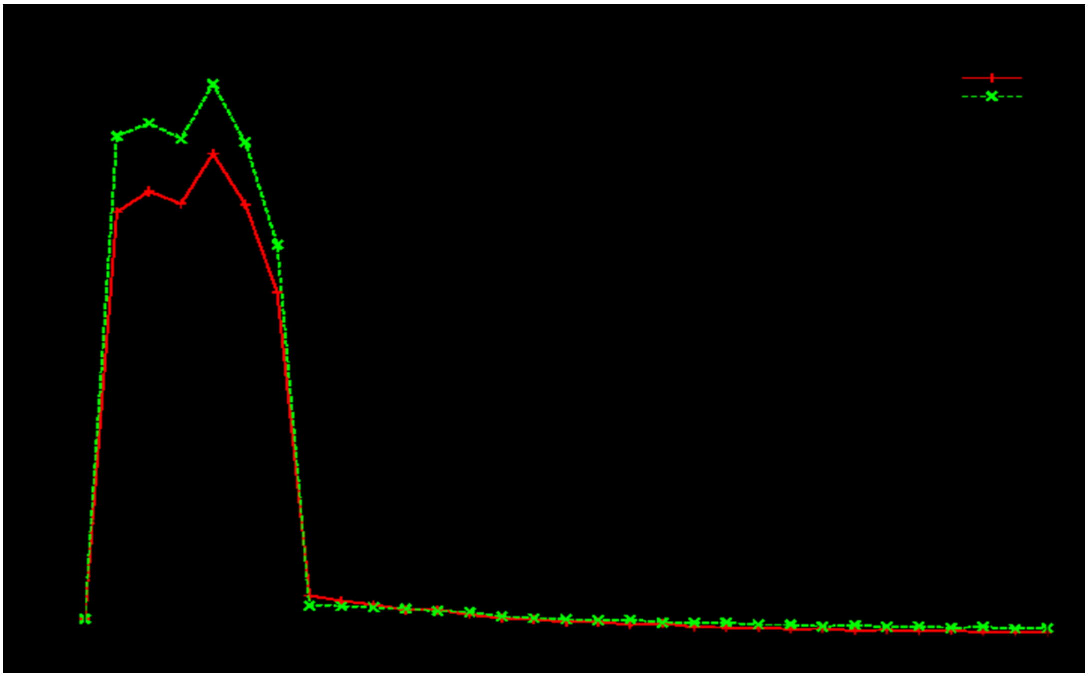


Figure 2.10 Simulation Result of 50 nodes in 100x100 meters

Literature	Publication & Year	Disadvantages	Future Enhancement
A Fast Converge cast Method for Tree-Based Wireless Sensor Networks	SECON '18, San Francisco, CA, USA,	Requires a centralized generated tree for scheduling	A proper tree generation method to attach with.
Energy Efficiency and Traffic Optimization through Data Aggregation in Wireless Sensor Networks	EEE MEMS Workshop, Nagoya Jan. 2016	Distributed Converge cast saves energy but in loss of latency	Require some better aggregation technique for saving latency as well as energy.
Event Aggregation with Different Latency Constraints and Aggregation Functions in Wireless Sensor Networks	IEEE 2014	Greater performance in terms of latency & energy saving but require already generated tree as input	A proper tree generation technique.
Delay Performance of Scheduling with Data Aggregation in Wireless Sensor Networks	IEEE 2016	Calculation of delay performance through different scheduling policies with help of maths.	The proven mathematics requires simulations for more clarity in results.
A Survey of Simulation in Sensor Networks	CIMCA, IWATIC & ISE 2015	Search of proper simulator which fulfill every requirement WSN is not over yet.	A proper simulator which gives more accurate results then current ones.
Efficient Data Aggregation in Multi-hop WSNs	IEEE 2013	This is a better technique for efficient aggregation but required proper scheduling policy to achieve latency.	A proper scheduling policy to schedule network.
Latency Optimized Data Aggregation Timing Model for Wireless Sensor Networks	IEEE International Conference 2014	A network directly target stent latency by ignoring energy constraint.	Requires technique to resolve energy scavenging issue.

2.11 Performance Parameters in Wireless Sensor Networks

The performance of WSNs is measured using various criteria, and the optimization of those criteria ensures the efficiency, reliability, and scalability of the network. Because WSNs run on low power, low bandwidth, and low processing capabilities, there is a need to give special attention to those criteria during the design process to develop an efficient communication protocol.

2.11.1 System Lifetime

System lifetime is one of the key performance criteria of WSNs. It is the period that WSNs stay alive after they have depleted their power sources. Normally, system lifetime is calculated based on the number of simulation rounds that occur before any node in the network stops functioning.

Since most sensors are mobile and have no external power sources, extending the system lifetime of WSNs becomes imperative. Efficient data transmission techniques and energy-aware scheduling algorithms are the most common methods used in enhancing system lifetime.

2.11.2 Latency

Latency is the time taken by data to travel from its source node to the sink node in a WSN. Latency is crucial for applications that require timely communication in WSNs, such as monitoring health situations, managing industrial activities, and detecting disasters.

Triggered events need instant transfer, but periodic sensing schemes do not necessarily need to be instantaneous. Nonetheless, high latency levels may affect system operations, causing decisions to be made later than required. Thus, designing low-latency systems that consume minimal energy is an important issue when developing WSNs.

2.11.3 Data Quality

Data quality indicates the extent to which the information received by the base station is accurate, relevant, and useful. In most cases, it is unnecessary for the final user to receive all the sensed information. Only meaningful data is needed to make decisions.

Factors affecting the data quality of WSNs include:
Effectiveness of data aggregation methods
Effectiveness of communication protocols
Effectiveness of sensing processes

A well-designed aggregation mechanism ensures that only significant data is transmitted, thereby improving both efficiency and usability.

2.11.4 Delay and Delay Variance

The term delay refers to the time required for the transfer of information between two nodes, and delay variance (jitter) denotes the difference in delay over time. There are several factors contributing to the delay in WSNs, including routing paths, congestion in the network, and scheduling algorithms.

Delay variance may adversely impact applications demanding stable data flow. Thus, stable delay performance becomes essential in such cases.

2.11.5 Bandwidth, Capacity, and Throughput

These terms refer to the capabilities of the network concerning data transmission:

Bandwidth: Maximum speed of data transmission through the network channel
Capacity: Total volume of data transmission
Throughput: Actual speed of successful data transmission

As far as WSNs are concerned, most data packets are quite small, and thus bandwidth cannot be considered a limiting factor. However, proper utilization of capacity becomes critical in preventing congestion.

2.11.6 Number of Hops

The number of hops is the number of intermediate nodes required for transmitting data from one node to another. It influences:

- Energy Consumption
- Delay
- Reliability

High number of hops increases the amount of energy consumption and delay. Optimized routing algorithms are designed to reduce hops so that there is an effective transfer of information between two nodes.

2.11.7 Signal Strength

The signal strength of the network can be used as an indicator of communication performance between different nodes. These measurements can be done using:

SNR (Signal to Noise Ratio)
RSSI (Received Signal Strength Indicator)

A higher signal strength results in a reliable connection between nodes and helps in identifying node reachability and stability.

2.11.8 Convenience of Installation

A WSN can contain multiple nodes from just a few to several hundreds. It is important that such networks function in an environment deprived of any infrastructure and require the self-organization of nodes for communication without any previous settings.

Convenience of installation makes it easy and fast to establish the network.

2.12 Faults in Wireless Sensor Networks

Because WSNs are deployed in difficult and uncertain settings, they are prone to different types of faults. Faults can negatively impact the efficiency and reliability of networks if not handled properly.

2.12.1 Node Faults

Faults at the node level happen because of faulty sensor nodes. These faults may be attributed to:

Difficult operating conditions
Hardware problems like antenna malfunction
Battery drain or leaks

These faults cause poor sensing and networking, leading to low performance of the entire network.

2.12.2 Network Faults

Network faults occur because of failed communications among nodes. The likelihood of packet collisions, interference, and link problems is high in dense networks.

2.12.3 Sink Faults

Sink fault is an important fault that acts as a data collector in the network. Any problem with the sink node, such as lack of energy or failure to communicate, results in total network failure since all communication occurs through this node.

2.13 Fault Tolerance Techniques

To achieve efficient communication, different techniques that tolerate fault are used in the WSN environment.

2.13.1 Retransmission

Retransmission is a fundamental fault tolerance technique where the packets of data are resent whenever there is a failure in transmitting them. The routing protocol chooses the most suitable route depending on the following two criteria:

- Minimal hops
- Low energy consumption

The receiving end sends an acknowledgment message when it receives the packets successfully.

2.13.2 Replication

In replication, the packets of data are sent along several paths at once. If one of these routes breaks down, then there is a chance for the packets to get to their destination through other paths.

2.13.3 Link Quality Indicator (LQI)

LQI evaluates the quality of a communication link by calculating its Packet Reception Ratio (PPR). This enables nodes to evaluate the link quality and decide whether to use it in the communication process or not. It is also applied in self-diagnosis.

2.13.4 Received Signal Strength Indicator (RSSI)

RSSI indicates the strength of the signal received in dBm. Its value varies from -45 dBm to -100 dBm. RSSI is used to analyze the quality of communication and discover faults.

2.13.5 Fuzzy Rule-Based System

This method integrates various factors including:

- Link quality indicator (LQI)
- Received signal strength indicator (RSSI)
- Number of hops
- Weight of a node

to make intelligent decisions about routing and detecting faults.

2.13.6 Agent-Based System

Under this technique, cluster node agents are employed for monitoring the health of the network. These agents assess various parameters like LQI and RSSI to identify any faulty node or cluster. This technique is especially effective in determining faults in extensive networks.

Table 2.1 : Summary of Performance Parameters, Faults, and Fault Tolerance Techniques in WSNs

Category	Parameter / Type	Description	Impact on WSN Performance
Performance Parameters	System Lifetime	Duration until network nodes exhaust energy resources	Determines network longevity and sustainability
	Latency	Time taken for data to reach sink from source	Critical for real-time applications
	Data Quality	Accuracy and usefulness of received data	Ensures meaningful decision-making
	Delay & Delay Variance	Time delay and its variation (jitter) in transmission	Affects reliability and consistency
	Bandwidth	Maximum data transfer rate of channel	Influences communication speed
	Capacity	Total amount of data that can be transmitted	Affects network scalability
	Throughput	Actual successful data transmission rate	Indicates network efficiency
	Number of Hops	Intermediate nodes involved in transmission	Impacts delay and energy usage
	Signal Strength (SNR, RSSI)	Quality of communication signal	Determines link reliability
	Convenience of Installation	Ease of network deployment and setup	Supports scalability and flexibility
Fault Types	Node Fault	Failure due to hardware issues, battery depletion, or environment	Reduces sensing and communication efficiency
	Network Fault	Communication failure due to collisions or interference	Causes packet loss and delay
	Sink Fault	Failure of central node collecting data	Leads to complete network failure
Fault Tolerance	Retransmission	Resending lost packets through optimal routes	Improves reliability

Techniques	Replication	Sending duplicate data via multiple paths	Ensures data delivery despite failures
	Link Quality Indicator (LQI)	Measures link quality using packet reception ratio	Helps in selecting reliable links
	RSSI	Indicates signal strength in dBm	Used for link stability analysis
	Fuzzy Rule-Based System	Uses multiple parameters for intelligent routing decisions	Enhances fault detection and adaptability
	Agent-Based System	Uses monitoring agents to detect faulty nodes/clusters	Improves fault management in large networks

2.14 Security Considerations in Wireless Sensor Networks

The problem of security is vital for WSNs, especially for those used in mission-critical applications like environmental sensing, health care, military operations, and industrial control systems. Given that WSN nodes function in open environments, they are extremely susceptible to many kinds of attacks. Securing the communications process within a WSN network becomes indispensable for maintaining the quality and reliability of the network.

A serious issue with WSNs is the fact that nodes have very limited computational capabilities as well as energy resources. It is impossible to use traditional approaches in terms of their resource consumption. Therefore, there is a need to employ more light-weighted security schemes.

Common security threats include:

- Eavesdropping: the interception of communications;
- Data tampering: alteration of data;
- DoS attack: denial of service; and
- Node capture attack.

In order to overcome the above problems, some security measures could be implemented:

Encryption Algorithms: Simple cryptographic schemes to secure data privacy
Authentication Schemes: To ensure that only legitimate nodes join in the communication process
Routing Security: To prevent any malicious node from interfering in routing
Intrusion Detection System (IDS): To detect any anomalous behavior within the network

From the perspective of the presented data transmission system, security can be incorporated in conjunction with the event aggregation and scheduling systems in such a way that only significant data is allowed to be transmitted.

2.15 Scalability and Network Adaptability in WSNs

One of the main requirements for WSNs is scalability. Scalability means that the network should still remain efficient concerning energy expenditure, latency, and throughput despite a changing number of network nodes (which might be a few sensors or thousands of sensors).

In large-scale WSNs, issues like higher communication costs, network congestion, and higher latency appear. Thus, protocols should have flexibility in adapting to the increasing size of the network.

The methodology proposed above ensures scalability because of:

- Hierarchical tree-based structure, which implies dividing nodes into dominators and dominatees, thus decreasing communication load
- Event aggregation, i.e., minimizing the amount of redundant data transfer, which is extremely important in densely-packed networks
- Efficient scheduling of transmissions based on TDMA or CDMA to minimize collisions and increase channel utilization
- Adaptive topology formation that allows creating centralized or distributed networks depending on the needs of a particular task.

- Network adaptability implies that a system is able to adjust itself to various changes, such as failures, power losses, etc. In WSNs, the number of nodes often changes; thus, a flexible approach to dealing with nodes is crucial for maintaining network functioning.

These are some of the main characteristics that enhance adaptability:

- Reconfiguration: Modifying the routing path whenever nodes fail.
- Load Balancing: Equal distribution of the communication load among nodes.
- Fault Tolerance Techniques: Providing fault tolerance and continuity of data transmission.
- Energy-Efficient Routing: Determining routing paths depending on the energy left in the nodes.

The presented data transmission system is scalable and adaptable due to the inclusion of the following: efficient formation of trees, event-driven communication, and effective scheduling.

2.16 Trade-off Analysis Between Energy Efficiency and Latency in WSNs

Optimal design of energy efficiency versus latency is among the most difficult and important issues in designing WSNs. This is because energy efficiency and latency have an inverse relationship in WSNs. Energy-efficient techniques always increase latency because they make use of buffering to aggregate data from different sources and duty-cycling and sleep-wake modes to avoid unnecessary transmission of redundant data. For example, in the data aggregation technique, multiple messages are aggregated to form a single message before being transmitted to the sink node. Although this greatly enhances energy efficiency through minimizing redundant transmissions, it increases latency due to the delay in aggregating sufficient information before transmission.

The sleep-wake cycle technique involves sleeping and waking up the radio whenever there is no data for transmission. During sleep mode, the nodes remain inactive, which results in energy saving. However, latency is introduced because of the need to wait for sufficient time to wake up the radio whenever there is data for transmission. In addition, data aggregation techniques cause a reduction in latency because of minimizing the number of redundant transmissions.

Alternatively, the problem of minimizing latency is concerned with fast transmission of information from the source node to the sink. Direct transmission, constant communication, and less buffering facilitate low delay. Nevertheless, these methods entail high energy expenditure due to multiple communications, more collisions, and high contention in the communication channel. Additionally, in dense sensor networks, there will be congestion, loss of packets, and reduction of the lifespan of the network.

Most of the earlier WSN protocols have always concentrated on maximizing one attribute out of the two (energy and latency) at the expense of the other. For instance, cluster-based protocols have been noted to stress energy saving through aggregation and cluster head rotation but cause high latency. The same case applies to reliable routing protocols, which concentrate more on delivering messages and cause extra energy expenditure through communication overhead.

In this regard, the suggested Rapid Data Transmission Technique attempts to overcome this weakness with the aid of a comprehensive approach that ensures efficient trade-offs between energy conservation and low latency levels. In particular, it uses event aggregation along with tree-based routing and intelligent scheduling processes. The process of event aggregation is essential since it sends useful data and not the entire raw data, thus cutting down any redundant communication without affecting the reaction to events.

On the other hand, tree-based routing minimizes the distance of transmission due to fewer hop counts. As such, this helps in minimizing energy consumption along with ensuring minimal latencies. The process of non-myopic and TDMA-based scheduling minimizes latency through preventing collisions during communication and thus ensures efficient channel usage. Through efficient scheduling of communication, the suggested technique ensures effective coordination of transmissions and no re-transmission of packets.

Moreover, the implementation of centralized backbone creation with distributed scheduling allows the system to respond effectively to different sizes and characteristics of the networks. Therefore, the balance between the amount of energy and latency can be adjusted accordingly to meet the current situation, as opposed to static setting used in other approaches. It should be noted from the simulation results that the method suggested performs much better in terms of latency when compared with the conventional schemes.

To sum up, the suggested scheme offers an effective solution to the problem of achieving balance between energy consumption and latency, due to its use of event-driven transmission, optimal routing architecture, and distributed scheduling. Such an approach can be successfully applied to real-life scenarios of WSN operation, namely, environmental control and industrial processes.

2.17 Problem Definition

Wireless Sensor Networks (WSNs) have attracted considerable attention because of their effectiveness in collecting data from the distributed network nodes. Nevertheless, existing data transmission schemes primarily emphasize energy conservation at the expense of latency, which is essential for real-time and event-driven applications. Conventional convergecasting and data aggregation methods can assist in minimizing unnecessary transmissions, but they add extra latency in terms of buffering, multi-hops, and ineffective scheduling.

The lack of a systematic approach to the design of the data transmission system, which includes tree construction, aggregation, and scheduling, results in problems like increased number of packet collisions, variable latency, and ineffective use of resources especially in massive WSNs. The main research problem that this study is going to address is the development of an optimal data transmission strategy for minimal latency and energy consumption.

2.18 Objectives and Scope of Work

The key purpose of this research is to develop "Rapid Data Transmission Technique for Wireless Sensor Networks (WSNs)" which would help address the challenge of balancing energy-efficiency and latency as previous approaches were limited to one or other side of the problem.

The suggested solution seeks to create a unified solution which would provide for fast and effective tree formation and data/event aggregation as well as efficient scheduling. Delay reduction, minimization of packet collision probability and improvement of network lifespan would be among top priorities in the process of creating such a solution. Non-myopic scheduling and smart event aggregation would significantly improve the performance of the solution on small and large scale.

This research covers both simulations and the initial real-time implementation of suggested ideas. It is planned to conduct an analysis of suggested techniques by means of WSN simulators in order to measure their impact on latency and energy consumption in different scenarios. Furthermore, there is going to be a basic test of real-time system on the basis of a simple sensor-based application, including such applications as gas leakage monitoring or indoor air quality measurement. The system would be first implemented with one sensor and then with multiple sensors.

Overall, the above-mentioned chapter covered all basic aspects of WSNs, such as the performance requirements, faults, ways of fault tolerance, as well as the main trade-offs in terms of energy efficiency and latency. Moreover, it became apparent that the current techniques in question have many weaknesses since they cannot address various problems at the same time. It is essential to emphasize that effective data aggregation, event-triggered communication, and intelligent scheduling play an important role in increasing the effectiveness of the entire network. In light of the above-mentioned information, there appears a clear necessity to establish a reliable data transfer technique. Thus, it can be expected that the following chapter will deal with the creation of the Rapid Data Transmission Technique.

CHAPTER – 3

Methodology

3.1 Methodology Overview

This study presents a mixed method, which involves both physical implementation and simulation, to develop the Rapid Data Transmission Technique for WSNs. The process starts with the implementation, followed by the design and evaluation of the technique through computer simulations.

The general goal is to make sure that the designed framework is feasible in practice, as well as theoretically efficient.

3.2 Physical Implementation

In order to evaluate the feasibility of the proposed framework in the real world, a communication model involving one sensor node and one sink node is implemented first. The purpose is to confirm whether data sensing, transmission, storage, and visualization are correct, before implementing a full-scale multi-sensor node WSN environment.

One possible application is a Gas Leak Detection/Indoor Air Pollution Monitoring System. Indoor air pollution is a significant issue that adversely affects the quality of life and may cause serious illnesses.

The implementation of the system involves:

1. MQ7 Gas Sensor: This gas sensor helps to detect the level of toxic gases such as carbon monoxide in the environment. It monitors the environment and generates an electrical signal based on the concentration of the gas.

2. NodeMCU Microcontroller: The NodeMCU microcontroller serves as the processor and transmitter unit in the proposed system. It captures the data generated by the sensor, processes the data, and sends it to a receiver wirelessly (via Wi-Fi).

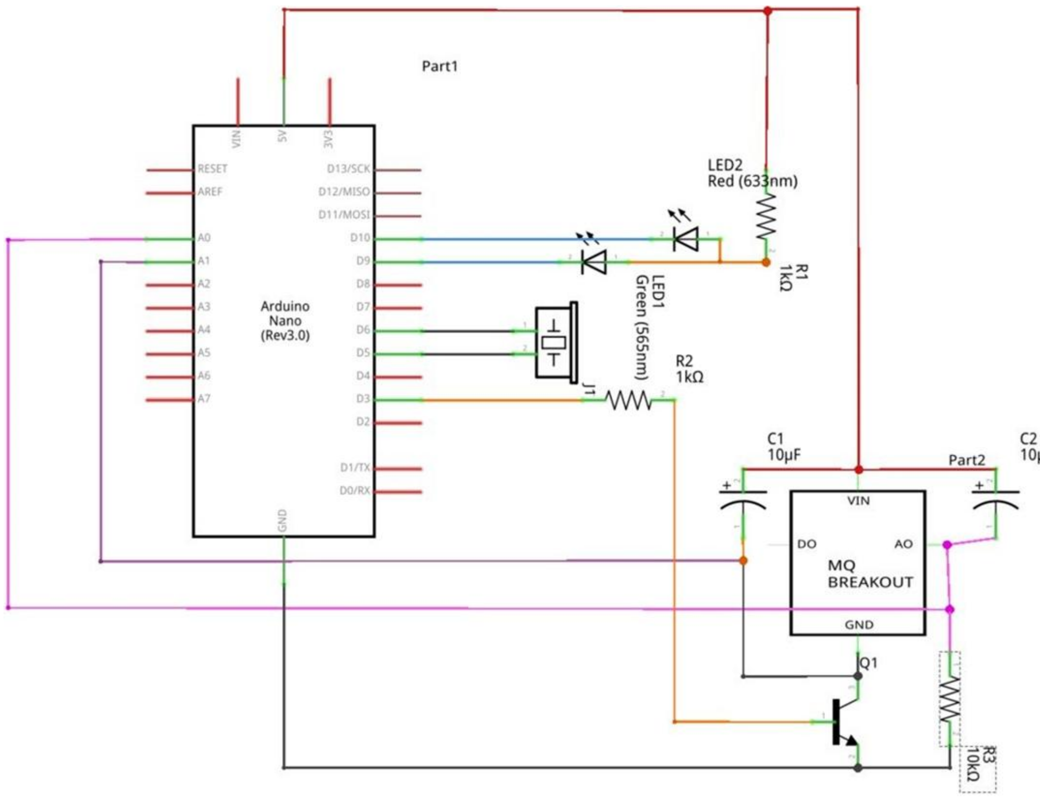


Figure 3.1 Logic Circuit for Controller Connections with Gas Sensor

The MQ7 sensor measures the levels of gases in real time. Data received from the sensors is then passed on to the NodeMCU to process and format it into messages for transfer. The NodeMCU then transmits the data to the cloud-based platform in which the data will be stored in spreadsheets or databases.

For easier interpretation and analysis, the data will be visualized through graphical interfaces such as graphs or dashboards. Visualization will enable one to track patterns, detect abnormalities, and issue notifications of any hazards due to high levels of gases.

Real-time monitoring of the environment is also possible within the framework of this project. Monitoring of the environment enables tracking and detecting any changes in the environment. This aspect makes the technology highly useful and applicable in several scenarios including smart homes, industries, and healthcare institutions.

The physical prototype represents proof-of-concept in this research. Proof-of-concept confirms that rapid data transmission, real-time monitoring, and data management are possible using the proposed technology before implementing the same in multi-node WSNs.

The data collected by the sensor node is not just sent out but is also processed, stored, and analyzed in order to make sense out of it. Once it is transmitted, the data is stored on a cloud storage platform using the spread sheet format. The data stored can then be used as the source of inputs in order to carry out various analyses which will show trends and patterns in the data. Charts and graphs are drawn in order to visualize the variations in the levels of gas concentration. Moreover, a dashboard interface is created in order to display the data in real time along with alerts regarding any deviation in the gas concentration levels beyond pre-set limits.

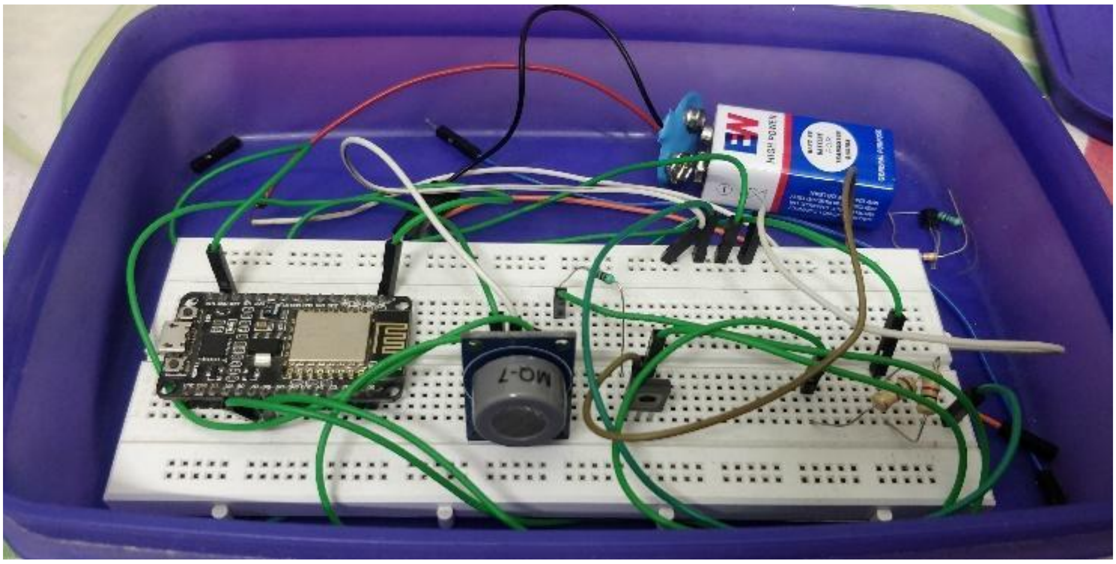


Figure 3.2 Physical Circuit Implementation

This figure 3.2 shows the physical layout of the proposed gas sensing system, showing the connection between the MQ7 gas sensor and the NodeMCU microcontroller. It showcases how the sensor measures the concentration levels of gases and then sends analog signals to the microcontroller. Appropriate interfacing between the power supply, signal pins, and the communication modules helps to facilitate efficient data collection. This is a key starting point in the process of proving real-time sensing and communication capabilities of the proposed system before developing a WSN network.

This figure 3.3 shows the physical layout of the proposed gas sensing system, showing the connection between the MQ7 gas sensor and the NodeMCU microcontroller. It showcases how the sensor measures the concentration levels of gases and then sends analog signals to the microcontroller. Appropriate interfacing between the power supply, signal pins, and the communication modules helps to facilitate efficient data collection. This is a key starting point in the process of proving real-time sensing and communication capabilities of the proposed system before developing a WSN network.

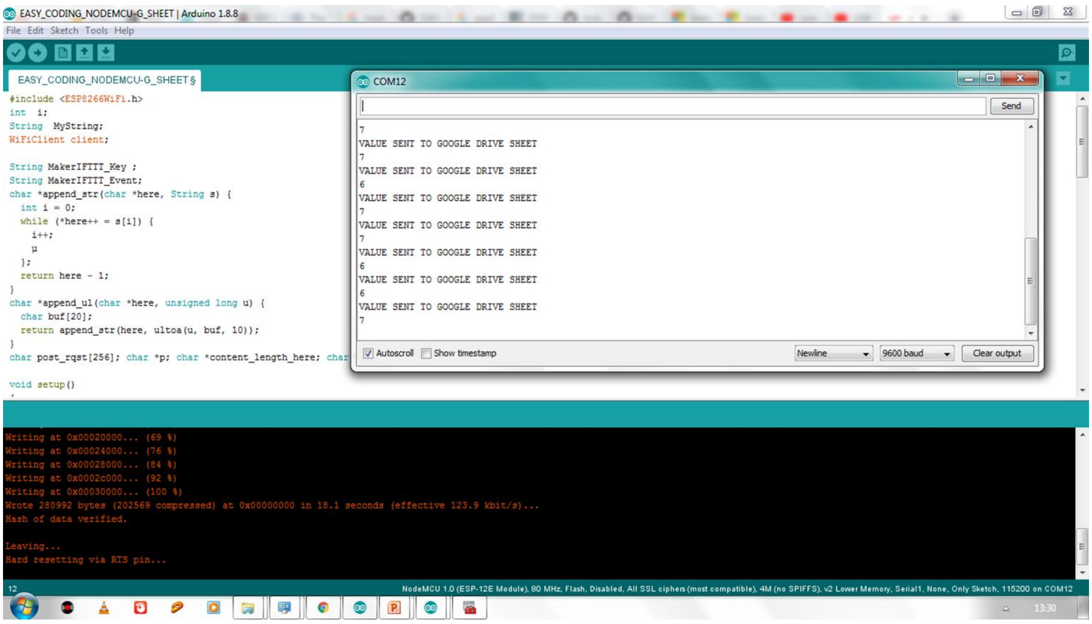


Figure 3.3 Sensor Data Transmission Output

This figure 3.4 illustrates the storing of the data that is collected by sensors and then transmitted to the cloud spreadsheet. The cloud server becomes the database to store and process all the received data. Cloud-based solution ensures flexibility and possibility of using the database remotely which makes it a suitable solution for IoT based applications including the presented environmental monitoring tool.

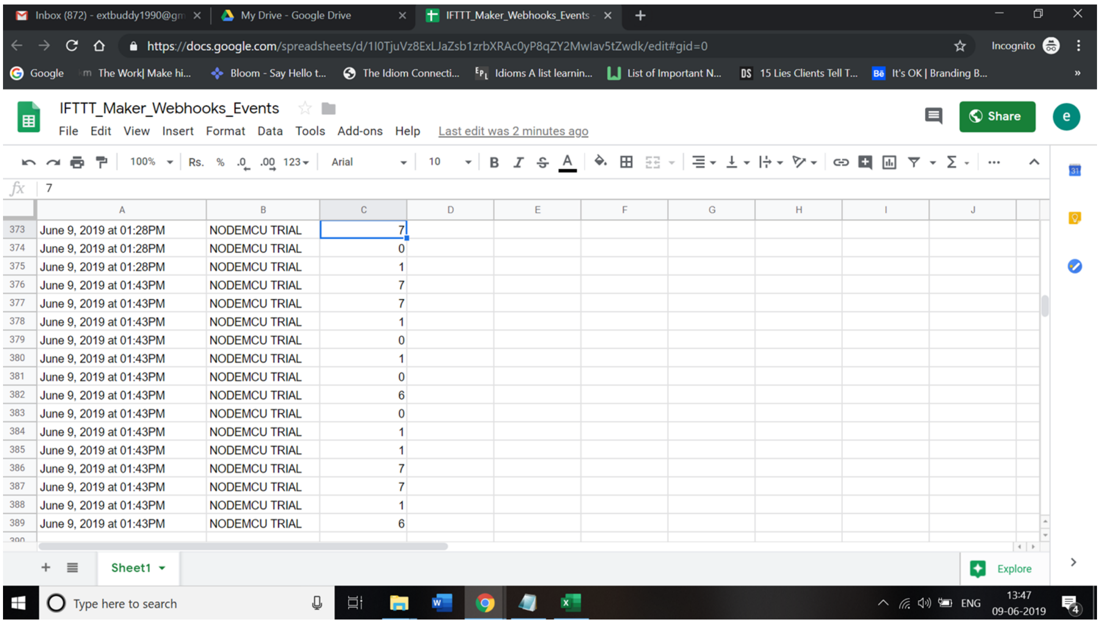


Figure 3.4 Data Storage in Cloud (Spreadsheet)

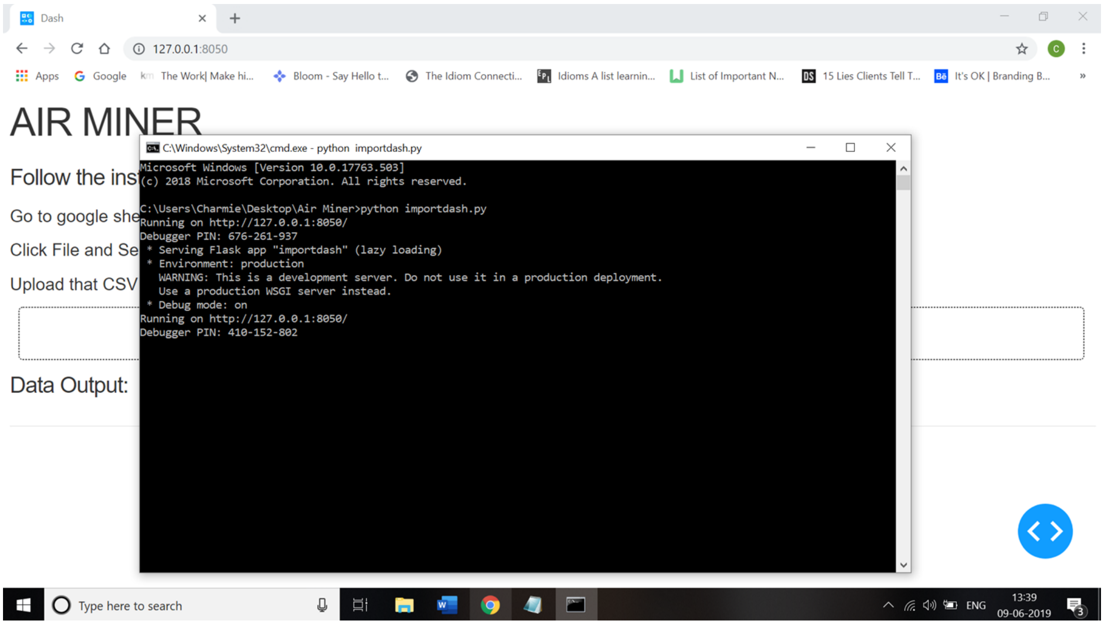
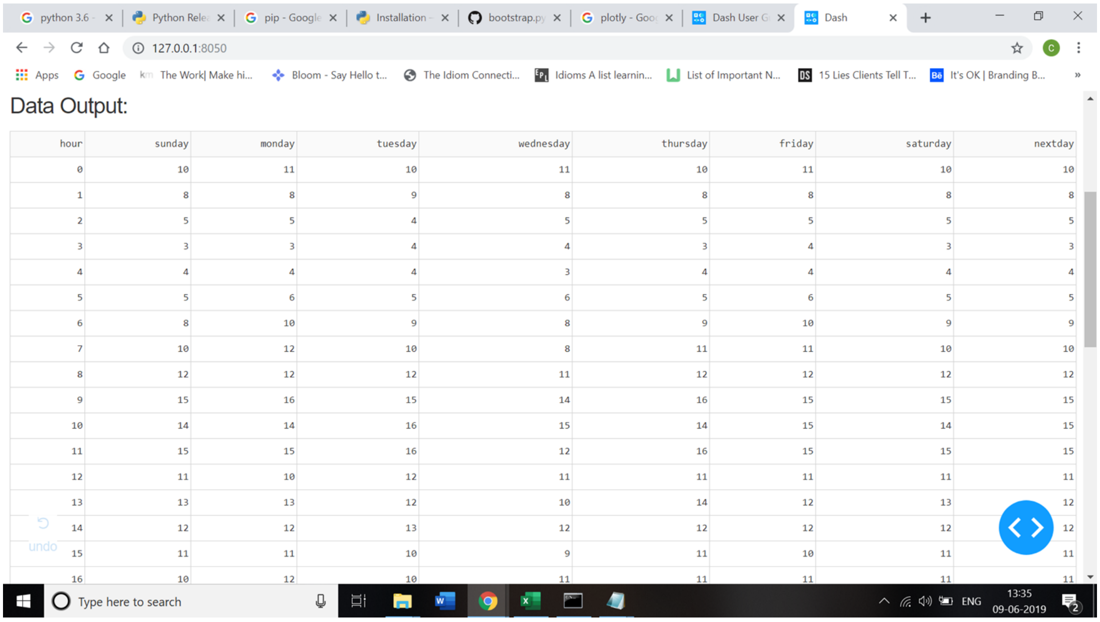


Figure 3.5 Sheet as an input for further analysis

This figure 3.5 depicts how the stored data may be used as an input source for further analysis. It is possible to calculate and analyze trends, identify anomalies in data readings and set up thresholds based on the available spreadsheet data. Such advanced data analysis allows obtaining insights from the obtained data.

This chart 3.6 shows the analysis process of the data gathered by the sensors throughout a week, which can be shown using charts and statistics. With this chart, it becomes possible to determine the patterns and trends of changes in the concentration levels of the gases. The process is vital in identifying any abnormalities and determining the environmental quality. The step highlights how effective the system is in analyzing the information collected.



hour	sunday	monday	tuesday	wednesday	thursday	friday	saturday	nextday
0	10	11	10	11	10	11	10	10
1	8	8	9	8	8	8	8	8
2	5	5	4	5	5	5	5	5
3	3	3	4	4	3	4	3	3
4	4	4	4	3	4	4	4	4
5	5	6	5	6	5	6	5	5
6	8	10	9	8	9	10	9	9
7	10	12	10	8	11	11	10	10
8	12	12	12	11	12	12	12	12
9	15	16	15	14	16	15	15	15
10	14	14	16	15	14	15	14	15
11	15	15	16	12	16	15	15	15
12	11	10	12	11	11	11	11	11
13	13	13	12	10	14	12	13	12
14	12	12	13	12	12	12	12	12
15	11	11	10	9	11	10	11	11
16	10	12	10	11	11	11	11	11

Figure 3.6 Weekly Data Analysis

This illustration presents the graphic presentation of the data acquired by the sensors, and gives us a basic sense of how different the levels of gas concentrations are. The chart displays the data collected by the sensors plotted on the timeline, making it easier for people to observe any changes that may occur. This kind of visual presentation is vital to the performance monitoring process, because through it, people can easily interpret massive amounts of information without having to go through numbers. Moreover, it also helps detect any unusual behavior, such as the sudden rise in the level of gas concentrations.

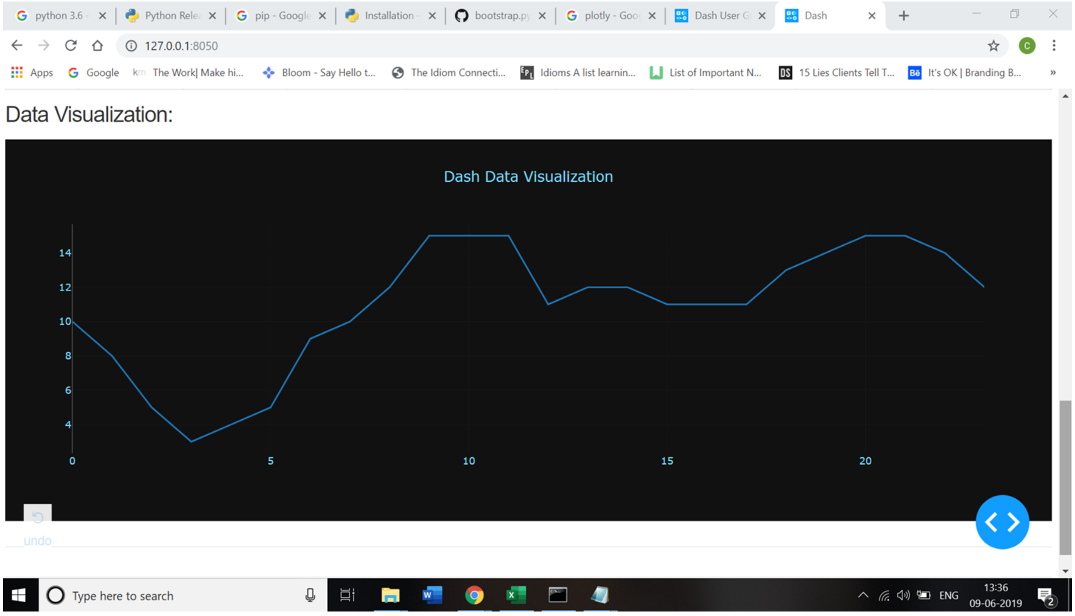
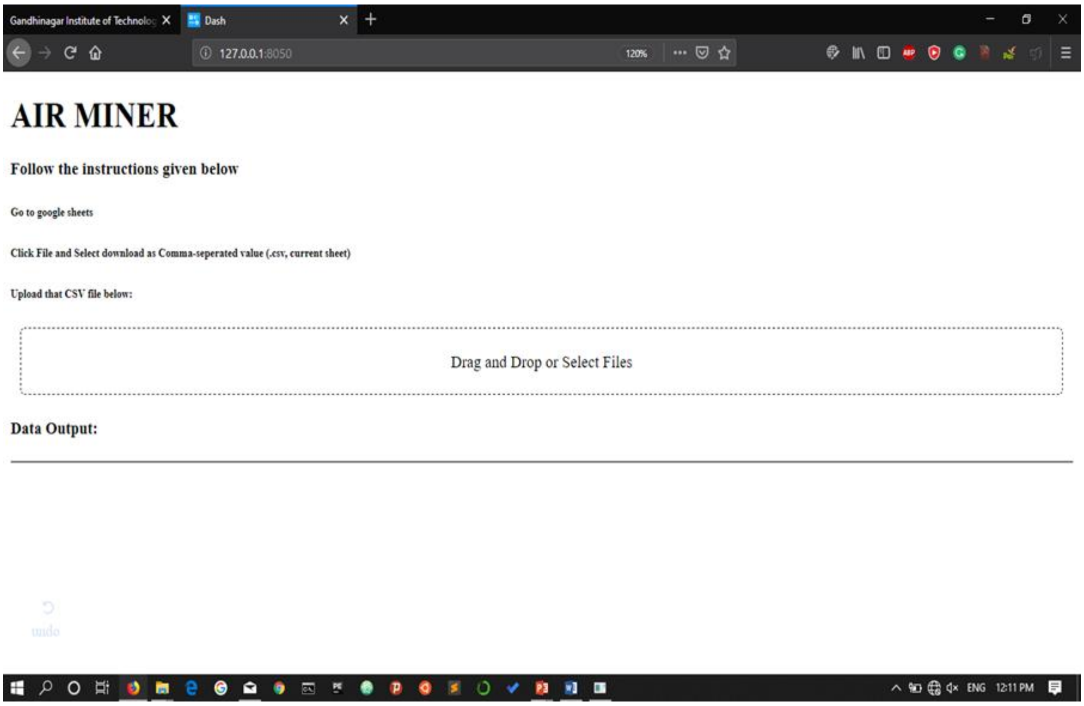


Figure 3.7 Graph Visualization



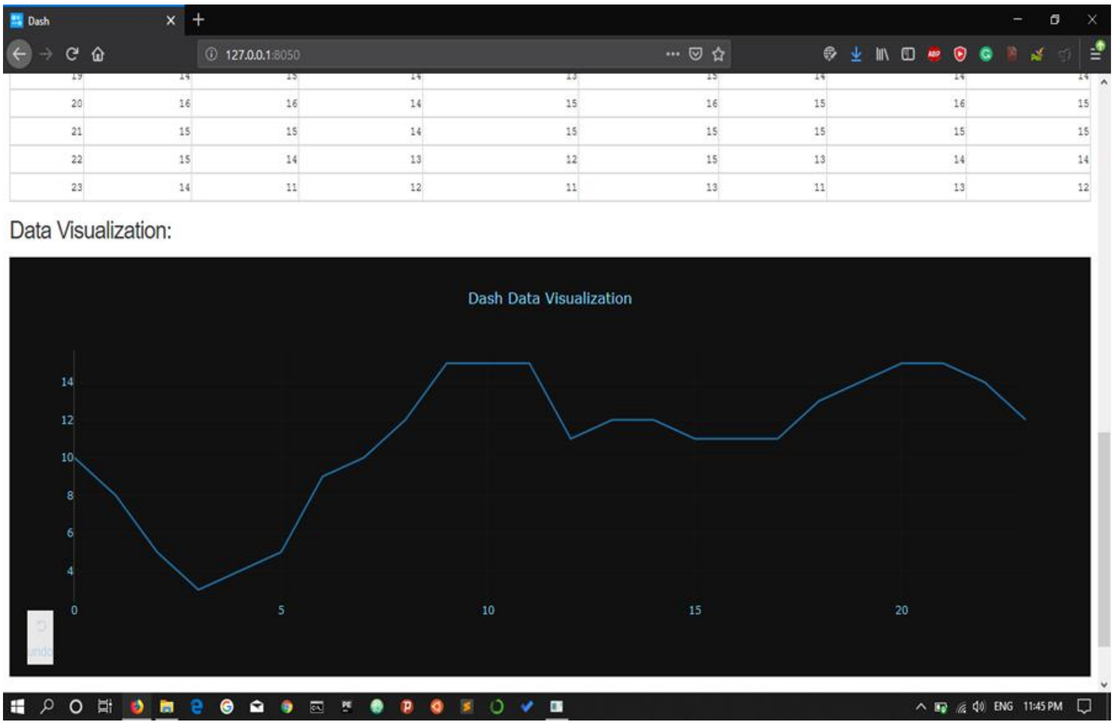


Figure 3.8 Dashboard and Alert System Interface

The following figure 3.8 shows the user interface of the dashboard with an alerting system for monitoring and decision making in real-time. The dashboard is an interface where the user can access live sensor information, trends of the sensor readings, and other important information related to the status of the system in one place. There are alerts based on thresholds in the interface, and whenever the threshold limit is crossed, the user is notified through messages or alarms. The user can interact effectively with the system using this interface to take prompt action in case of emergencies.

3.3 Proposed Methodology

The proposed method is intended for quick and efficient data transfer through the use of tree-based routing algorithm, data aggregation, and intelligent scheduling. Such integration makes it possible to meet the two main criteria of WSN, namely low latency and low energy consumption.

This is achieved through minimization of redundant transfers and data collisions, as well as improvement of data communication efficiency. The entire process takes place with the help of an aggregation tree through which all the data is transferred from sensors towards the sink.

3.3.1 Network Topology Configurations

Network structures' impact on performance is examined through different placement schemes for base stations.

A corner network structure places the sink node at the edge of the network. As a consequence, there is an increase in the average hop distance, which results in greater energy consumption and delay.

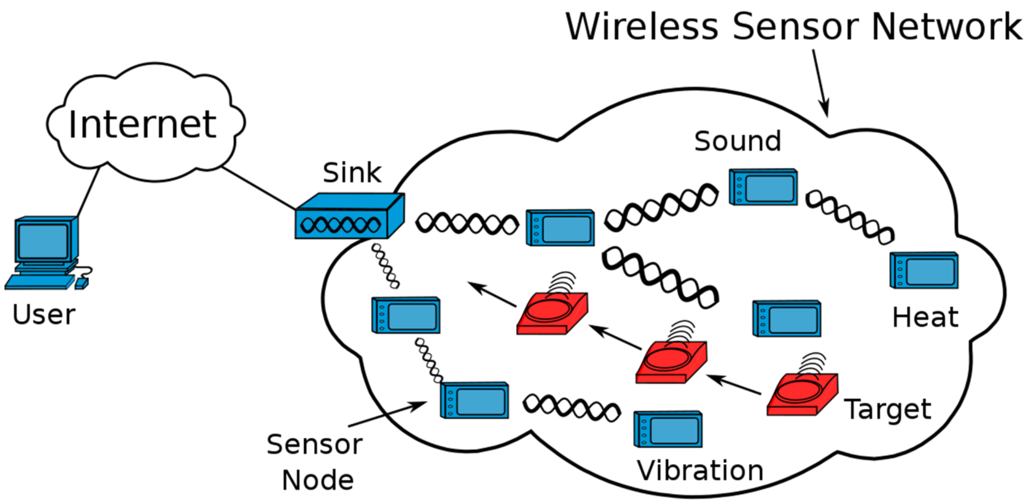


Figure 3.9 Base Station Placement in Corner Topology [19]

On the other hand, in a centralized network structure, the sink node is placed in the middle of the network. It causes a reduction in the average hop distance and thus helps improve latency and energy consumption.

Moreover, the network structure is based on an underwater sensor network to study the worst-case scenarios in terms of communication.

3.3.2 Collision Avoidance and Efficient Communication Techniques

In order to facilitate efficient communication in WSNs, it is necessary to reduce the occurrence of collisions and avoid redundant transmissions. To achieve this, several communication strategies are included in the designed scheme.

The RTS/CTS strategy allows for controlling the channel access through which the nodes can send messages to other nodes only when receiving an authorization message, thus preventing collisions from occurring.

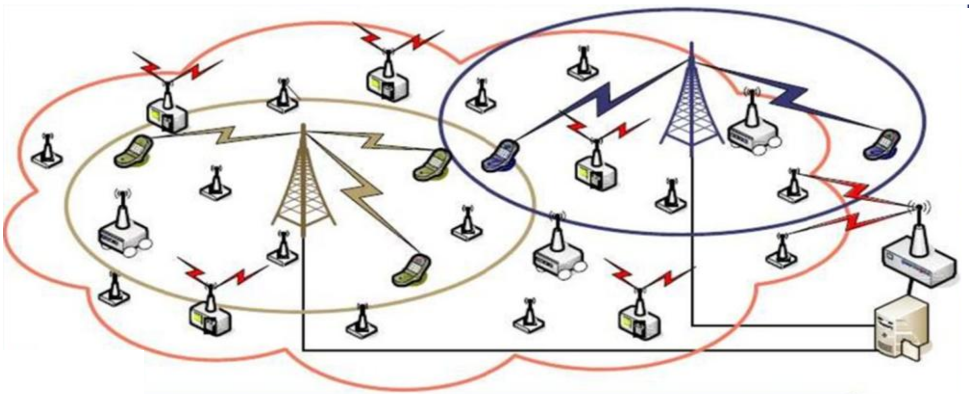


Figure 3.10 Base Station Placement in Centralized Topology [19]

Moreover, the MACA protocol provides additional support in this regard by implementing a handshaking process among the nodes prior to data transmission.

Furthermore, CDMA and TDMA approaches are utilized for improving channel efficiency by employing unique coding schemes assigned to each node in the CDMA approach and assigning time slots for each node in the TDMA approach.

3.3.3 Energy Efficient Scheduling Scheme

In addition, an efficient scheme that combines sleeping and waking up of nodes is proposed for improving performance.

Communication consists of two phases:

- Setup Phase – Clustering & Scheduling
- Steady-State Phase – Data Transmission

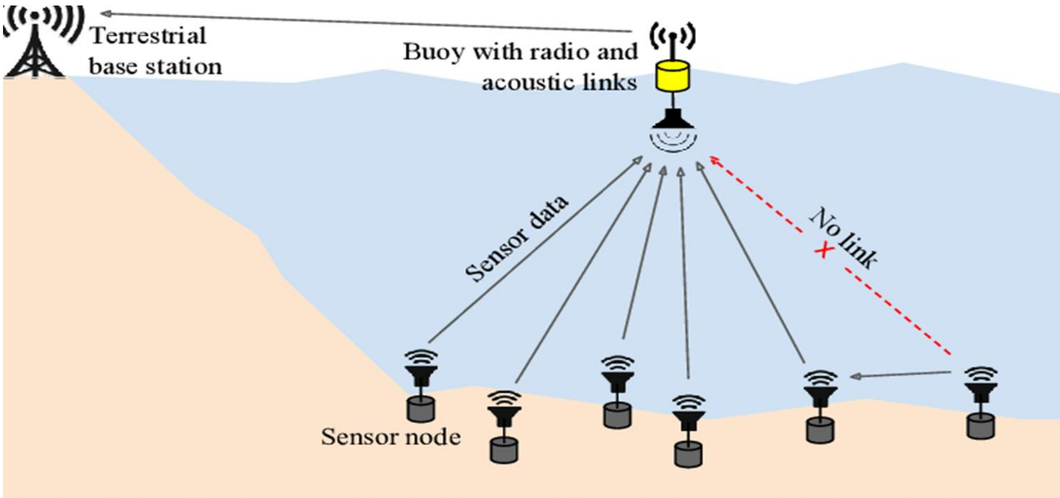


Figure 3.11 Underwater Sensor Network Topology [19]

In the active phase, the nodes are involved in communication activities, whereas in the sleeping phase, they save energy by performing no activity. This results in low energy consumption without compromising the data transmission rate.

3.4 Collision Avoidance and Efficient Communication Mechanisms

In WSNs, it becomes imperative to facilitate efficient communication channels, allowing the fast and reliable exchange of data. The shared nature of the wireless medium often causes collisions of packets sent from multiple sensors, thereby causing delays and wastage of energy due to retransmission attempts. It therefore becomes highly important to implement efficient means of avoiding such problems and increasing the speed and quality of communication in the network.

For this reason, the suggested framework utilizes several different methods of controlling communications to achieve maximum efficiency and prevent any unnecessary conflicts. One of the key strategies implemented in the system is the use of the RTS/CTS (Request to Send/Clear to Send) protocol. In accordance with this protocol, prior to sending actual information, the sender sends an RTS request to the destination address and receives an appropriate response in the form of a CTS signal, allowing the node to start transmission. This way, neighboring nodes receive a signal about the ongoing transmission, reducing the chance of collision.

One additional mechanism implemented is the MACA (Multiple Access with Collision Avoidance) protocol, which is a more sophisticated approach based on the RTS/CTS protocol. MACA provides an orderly way of accessing the communication medium through a coordinated manner of transmissions. Through this, MACA makes sure that there is no more than one dominant node accessing the medium per time. It helps in minimizing collisions and increasing reliability of transmissions.

Apart from these mechanisms, other advanced multiple access protocols like CDMA and TDMA are used to increase efficiency of communications.

- Code Division Multiple Access (CDMA):
  Through CDMA, each dominatee node is assigned a particular unique code. Transmission of several dominatees over the same channel simultaneously is possible since each message is distinguished by the receiver by its code.
- Time Division Multiple Access (TDMA):
  In this case, time is divided into slots, and each node is assigned a time slot during which it should transmit messages. Through this, no two nodes transmit messages at the same time; therefore, it results in collision-free communication. The great thing about TDMA is its high efficiency because nodes activate for their time slots only and sleep in other times.

Moreover, in this regard, the suggested scheme employs an organized form of data transfer from the dominatees to the dominators to enable effective hierarchical data aggregation. In this case, the transmission of data occurs from subordinate nodes to the dominant nodes whereby the data aggregation process takes place, after which it will continue to be forwarded to the destination node. In addition to the above, sleep-wake scheduling is adopted to further enhance the operation of the network. Under this arrangement, each node operates in either the active or the sleep mode whereby during the active period, nodes transmit messages while during the sleep period, they remain inactive. Scheduling is done in two stages; setup and stable states. At this point, transmission synchronization signals such as RTS, CTS, and scheduling broadcasts are used.

On the whole, the use of RTS/CTS, MACA, CDMA, TDMA, hierarchical data flow management, and sleep/wake scheduling facilitates effective and reliable communication in

WSNs. This will ultimately contribute to minimizing collisions and maximizing channel utilization in the system as a whole.

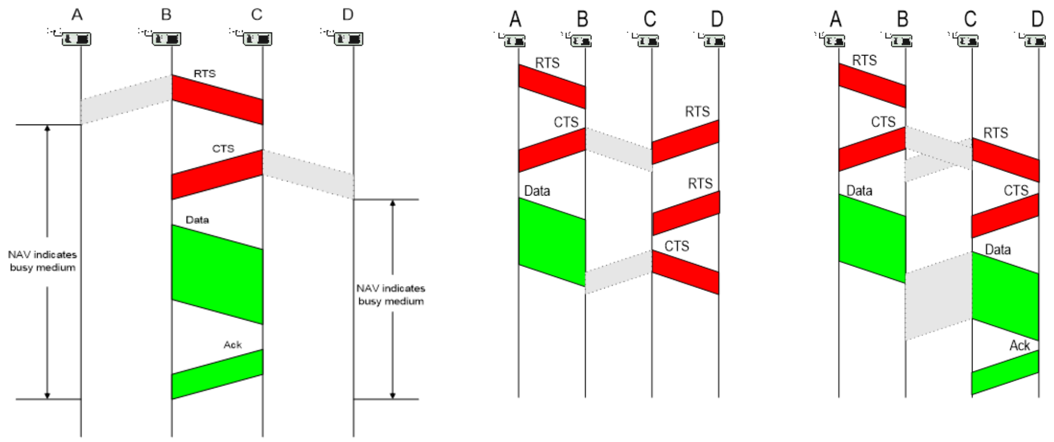
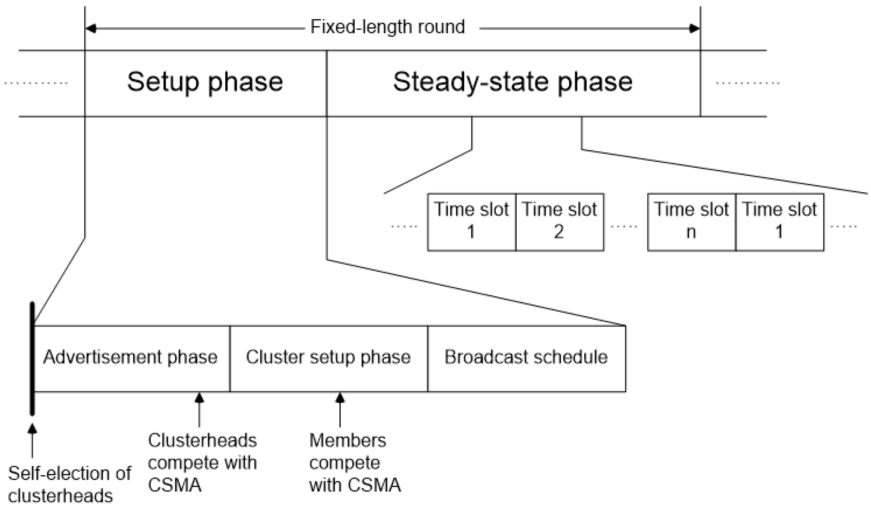


Figure 3.12 MACA-Based Collision Avoidance Mechanism

This figure 23 shows the data flow from dominatees to dominators, ensuring smooth aggregation and transmission.



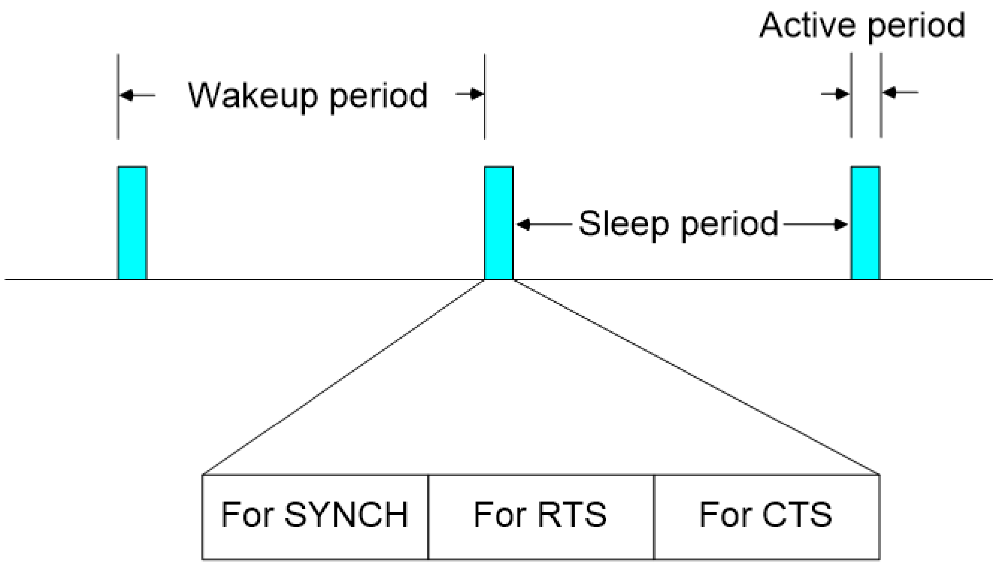


Figure 3.13 Sleep–Wake Mechanism for Energy Efficiency

Table 3.1: Comparison of WSN Simulation Tools

No.	Simulator	Platform / Language	Description	Limitations
1	NS-2	C++	Easy to add new protocols and widely used for general network simulation	Supports only a limited number of wireless MAC protocols
2	TOSSIM	C	TinyOS-based simulator specifically designed for WSN applications	Limited scalability and hardware abstraction
3	SensorSim	C++	Extension of NS-2 with additional support for sensor network modeling	Complex implementation and higher computational overhead
4	Atemu	Java	Emulator for AVR-based sensor nodes enabling hardware-level simulation	Limited support for large-scale network simulations
5	Avrora	Java	Cycle-accurate simulator for	High computational complexity and

			embedded sensor platforms with detailed energy profiling	slower execution
6	Castalia	C++ (OMNeT++)	Provides realistic wireless channel modeling and node behavior simulation for WSNs	Requires detailed parameter tuning and configuration
7	J-Sim	Java	Component-based simulation environment for WSN and general network protocols	Limited documentation and community support
8	MATLAB/ Simulink	MATLAB	High-level modeling, analysis, and visualization of WSN algorithms	Not suitable for packet-level or large-scale network simulation
9	QualNet	C++	High-performance simulator designed for large-scale wireless network analysis	Commercial software with licensing cost
10	OPNET	C++	Advanced network simulation tool with detailed protocol and performance modeling	Expensive and complex to use

3.5 Proposed Algorithm

The presented data gathering algorithm will be implemented through a greedy and hierarchical method for the sake of achieving efficient and quick data transfer in WSNs. The idea behind this methodology is that each dominatee sends its data to the dominator located nearest to it for minimizing both the cost and time.

This procedure takes place in a hierarchical manner in such a way that data aggregation begins at lower layers and continues at higher layers until reaching the root of the aggregation tree (or topological center). Finally, the data is transferred to the sink node via the shortest route.

Working Principle

- The dominatees choose the closest dominators (greedy algorithm)
- Data aggregation occurs in intermediate nodes
- Aggregation takes place layer by layer towards the root node
- The final aggregated data will be sent to the sink

This process guarantees reduced redundancy, better energy consumption, and lower latency.

Algorithm Phases

Phase 1: Data Aggregation to Dominators (Advertising Phase)

This phase focuses on collecting data from dominatee nodes.

For each iteration $i=1$ to Δ:

1. Each dominator selects one neighboring dominatee whose data has not yet been collected
2. These communication links form a set L
3. If conflicts occur among links in L, they are resolved using Phase 2
4. All non-conflicting links transmit data simultaneously
5. The process repeats for the next iteration

This phase enables parallel and efficient data transmission.

Phase 2: Reconnection of Dominatees

This phase ensures network connectivity by resolving conflicts.

1. Repeat while interfering links exist
2. Select a conflicting pair of links (u_i,z_i) and (u_j,z_j)
3. Identify corresponding sets D_i and D_j

4. Establish alternative non-conflicting links

This phase guarantees that all nodes are properly connected without interference.

Phase 3: Centralized Backbone Construction (EAS)

In this phase, an optimized aggregation tree is constructed.

1. Build an event aggregation tree T′ using the CDS approach
2. Remove redundant connector nodes while maintaining connectivity
3. Ensure each dominator connects within a 2-hop distance

   Then for each level i = R − 1 down to 0:

4. Identify dominator set BiB_iBi
5. For each node u∈Biu \in B_iu∈Bi, determine D2(u)D_2(u)D2(u) (2−hop dominators)
6. Mark nodes in $D_2(u)$
7. Each node transmits aggregated data using function f(Aw,X1,X2,…,Xd)f(A_w, X_1, X_2, …, X_d)Connector nodes forward aggregated results upward
8. Repeat for all levels

Finally, the root node v0v_0v0 sends aggregated data to the sink using the shortest path.

Phase 4: Distributed Scheduling (TDMA-Based)

This phase assigns transmission slots to avoid collisions.

Input: Network GGG, Aggregation Tree T
Output: Time slot TST[i] for each node

Steps:

1. Each node initializes:
   - Number of children NoC[i]
   - Leaf status Leaf[i]
2. Construct conflict set CS[i]

3. Compute ready set:

   RdyCS[i]=CS[i]∩{leaf nodes}
4. Initialize:

   TST[i]=0, DONE = FALSE
5. Generate random priority rir_iri
6. While DONE = FALSE:
   - If NoC[i]=0, broadcast READY message
   - If highest priority, send FINISH message and mark DONE
   - Update time slot:

     TST[i]=max(TST[i],TST[j]+1)
   - Update child count and ready sets
7. Node transmits data in assigned time slot
8. Root node forwards final aggregated data to sink

This phase ensures collision-free and efficient scheduling.

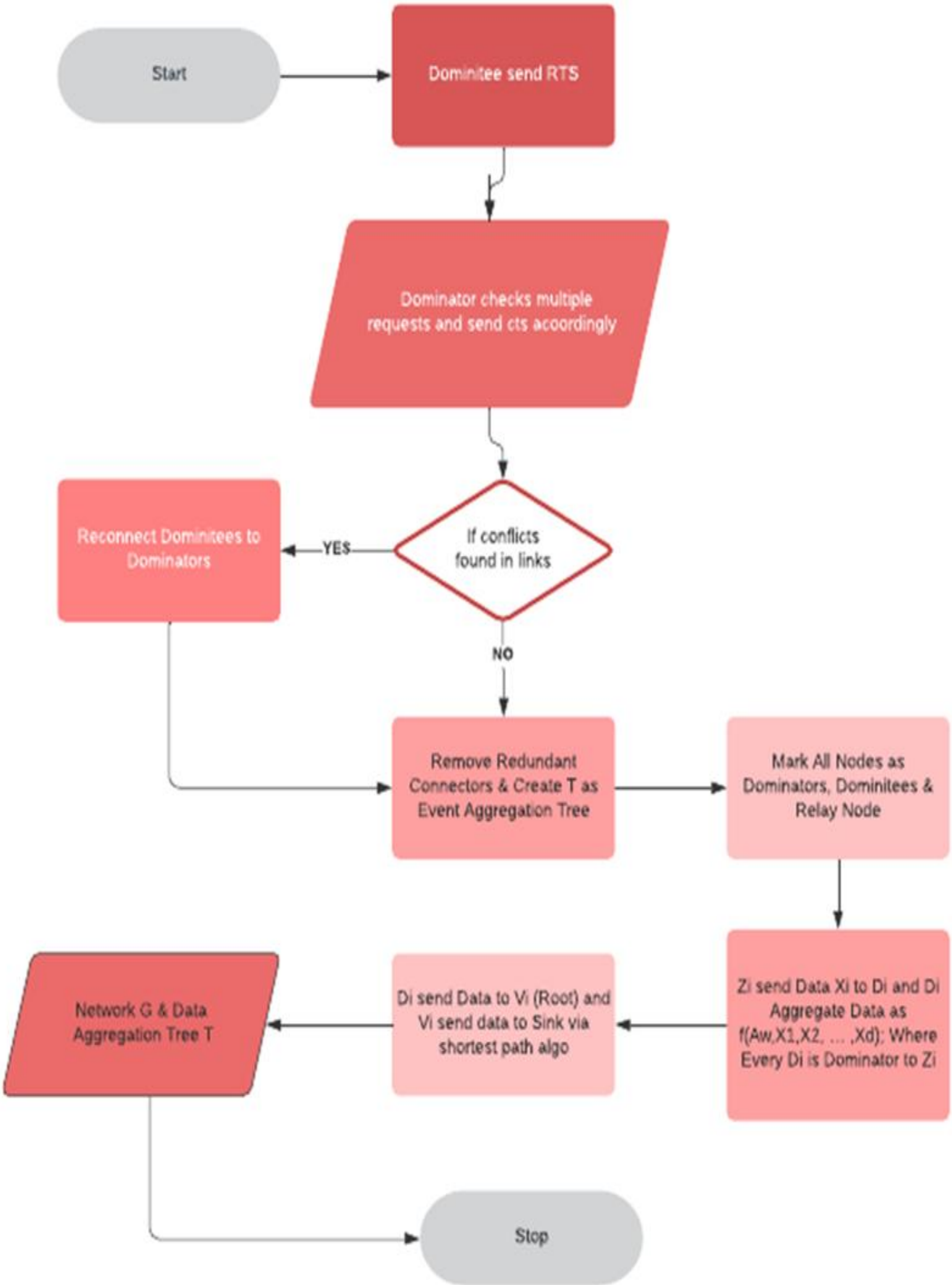


Figure 3.14 Flow chart for aggregation Tree Generation

This event aggregation tree generation method aims at organizing the nodes in the WSN in a communication infrastructure that would consume minimal energy, lower latency, and avoid any form of packet collision. The method employs the combination of greedy, hierarchical aggregation, and conflict avoidance principles in generating an optimized event aggregation tree.

1. **Network Initialization and Node Classification:**

   Firstly, the network deployment entails placing multiple sensor nodes in a predefined environment. Each node is classified as either a dominator or dominatee based on the network's physical configuration. Dominatees have the role of collecting and forwarding information from their immediate environment while dominators aggregate and route the collected data. This categorization forms the basis for hierarchical communication. The process starts by ensuring that each node has information regarding its neighbor nodes and communication settings.

2. **RTS Communication Request**

   In order to create communication channels, dominatee nodes make the first move and send out Request To Send (RTS) signals to the neighboring dominator nodes. This procedure facilitates the determination of the potential channels and prevents blind transmission of data packets. With the involvement of several dominatees in the simultaneous transmission of data, this process enables an orderly process of communication based on request.

3. **CTS Channel Establishment**

   The dominator nodes, upon receiving the RTS signals, analyze the requests received from the different dominatees and then send back Clear To Send (CTS) signals to some of the dominatees. This action creates a stable communication channel between the dominatees and dominator nodes while ensuring that several nodes do not transmit their data on the same channel at the same time.

4. **Identification of Interference and Link Conflict**

   In the second step, after establishing a connection, the algorithm analyzes conflicts between different communication links. A conflict arises in case more than one transmission interferes with each other because of common communication range and channel overlap. This step is essential for guaranteeing data transmission efficiency since otherwise, packet losses and higher delays could arise due to interference.

5. **Interference Resolution by Reconnection**

If there are any conflicts, then an algorithm implements a reconnection scheme. This is the stage where conflicting connections are analyzed and new dominators and links are assigned to affected dominatees. The process goes on repeatedly until all conflicts have been solved.

6. **Optimization Through Elimination of Redundant Connectors**

The next step in this algorithm involves optimization of the network through the elimination of redundant connectors. These connectors are basically nodes which are not important for keeping the connectivity of the network. This will make sure that there are fewer levels in the aggregation tree and thus minimize both power consumption and data transfer time. It should be noted that the final result after optimization will be known as Event Aggregation Tree (T).

7. **Classification of Nodes and Hierarchical Structure**

The final step involves classification of nodes in a certain network hierarchy:

- Dominators as aggregators;
- Dominatees as generators; and
- Relay nodes to help in transferring data between levels.

It is clear that this arrangement allows for an organized transfer of data from lower level nodes to higher level nodes.

8. **Data Aggregation by Intermediate Nodes**

During this stage, the dominatee nodes send the collected data to the corresponding dominators. The dominators aggregate the data using an aggregating function to get one output value from the multiple input values. Rather than sending the collected data, the nodes send the aggregated data to other nodes. This helps greatly in saving the transmission process.

9. **Hierarchical Data Transfer**

After being aggregated, the collected data is transferred hierarchically from one level to another as follows:

- From dominators at lower levels
- To dominators at higher levels
- To the root node (topology center)

This process guarantees that the network is optimally used.

10. Last Transmission to Sink Node

The root node, acting as the aggregation node, transmits the last aggregate data to the sink node. The application of the shortest path algorithm guarantees the fastest transmission of data and minimal energy usage in doing so. This marks the completion of the data transmission process.

11. Construction of Graph and Aggregation Tree

Output from this algorithm consists of:

Graph G, denoting node connections

Aggregation tree T, denoting data flow pattern

This defines the entire network communication model in the WSN, which will facilitate continuous data transmission.

12. End Point and Continuous Operation

When the aggregation tree is generated and the data transmission process completed successfully, the algorithm ends. But in reality, this process has to be performed regularly depending on network dynamics such as malfunctioning nodes, depletion of energy resources, or environmental factors.

The new tree construction algorithm successfully merges conflict-based communication, hierarchical aggregation, and structural optimization into a unified scheme for improving the performance of WSNs. Communication conflicts can be detected and avoided by the algorithm, ensuring interference-free and reliable data transmission in WSNs. The hierarchy-based data aggregation technique helps to minimize the amount of data sent by aggregating data at intermediate nodes. Furthermore, unnecessary connector links can be eliminated to optimize the topology of WSNs. Consequently, the proposed solution can minimize data transmission delays to deliver data more efficiently, conserve energy by reducing data communication traffic, scale up to handle large network systems, and ensure stable data communication without interference.

The above figures provide more insight into the process of constructing and organizing the aggregation tree employed by the proposed methodology. The first one depicts a hierarchical layered aggregation tree with sensors positioned in several layers moving upwards from leaf nodes up to the sink node located in Layer 0. Each layer represents the logical proximity to the sink, with all data transmission taking place in an upward direction from intermediate nodes that include dominators and connectors. Dominators are represented by black circles and are responsible for aggregation tasks, whereas dominatees are represented by white circles, and their task is to transmit data.

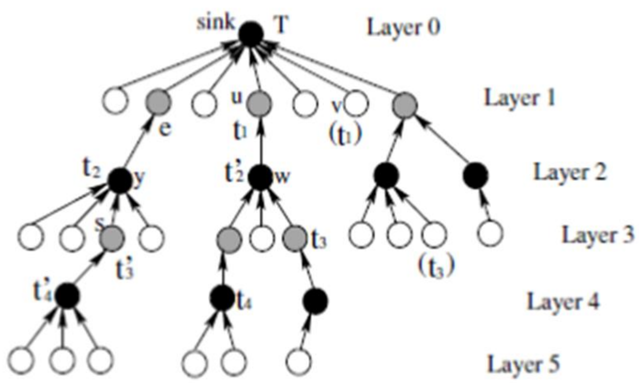


Figure 3.15 Hierarchical layered aggregation tree structure showing multi-level data transmission from sensor nodes (dominatees) to dominators and finally to the sink node.

The layered organization allows for efficient multi-hop transmissions and prevents any unnecessary duplications, thus allowing systematic aggregation of data in each layer until its delivery to the sink. The transmission schedule is marked with the help of time slots such as t_1, t_2, t_3, and others.

The network is partitioned using region-based clustering, which is almost like Voronoi tessellation. In this method, the whole area covered by the sensors is subdivided into several irregular regions, wherein each region has a dominating node called cluster head or dominator. The process of creating such regions is guided by the distance between the sensor nodes and the nearest dominator. It ensures that the node transmits its message to the closest dominator. As a result, the communication distance becomes shorter; thus, the energy consumed during the process is minimized, and the lifetime of the network is optimized. Irregular shapes seen in the image are actually formed clusters wherein nodes automatically cluster with the closest dominator and move away when the conditions are not favorable. This automatic behavior enables the efficient management of network loads so that no dominator experiences an overload due to high communication demands. Furthermore, this process of spatial division helps confine the data transmission to specific zones, and hence, minimizes any form of interference, collision, or congestion on the network. With the increase in the number of nodes in the network, this clustering algorithm will ensure that resources are efficiently utilized in order to maintain stability of performance, due to the fact that the tasks will be distributed equally across the entire network.

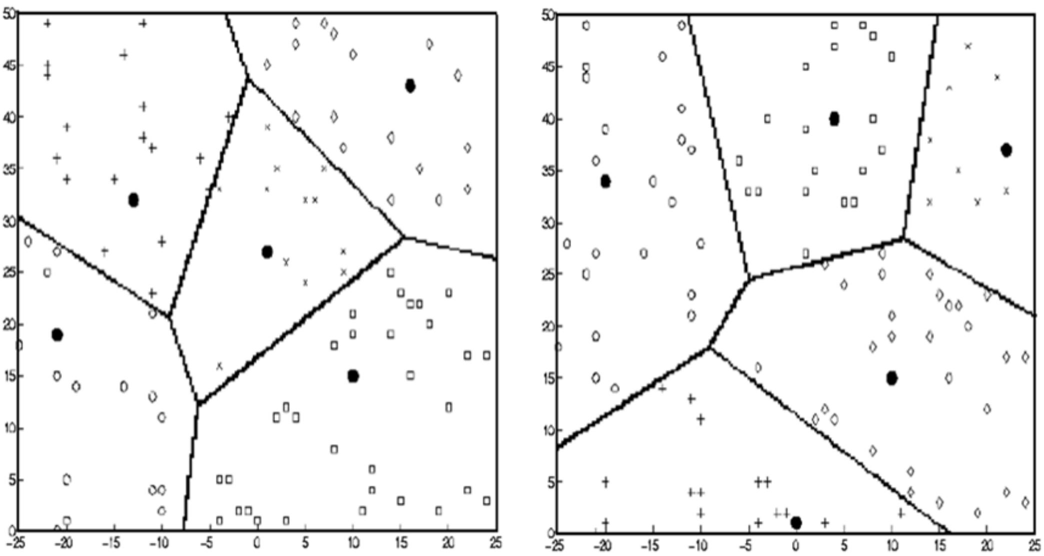


Figure 3.16: Region-based spatial clustering of sensor nodes using Voronoi-like partitioning for efficient communication and load balancing

This chapter discussed the design and implementation of the Rapid Data Transmission Technique for Wireless Sensor Network. As can be observed, the proposed methodology involves both practical implementation of the design as well as the theoretical aspects. Starting from physical implementation involving an actual device like the use of NodeMCU microcontroller and the MQ7 sensor as well as ending at the design algorithm that can accommodate all aspects involved in data transmission process. As can be observed, the proposed methodology involves components that include network topology design optimization, formation of hierarchical aggregation trees, and efficient collision avoiding mechanisms. As already noted, clustering of nodes and layers of aggregation makes sure of systematic organization of communication among other important elements. Involvement of protocol schemes like RTS/CTS, MACA, TDMA, and CDMA among others makes sure of reliable and conflict free data transmission process. Additionally, the proposed aggregation and scheduling phases involve efficient and effective data flow from sensor node devices to sink. This is brought by use of greedy and hierarchical approach towards data flow and management. All this will make sure of reduced redundancy, energy efficiency, and latency.

CHAPTER – 4

Results and Discussion

4.1 Introduction

The performance of the proposed Rapid Data Transmission Technique for Wireless Sensor Networks (WSNs) is evaluated using extensive simulations carried out in Castalia and NS2 environments. The evaluation focuses on key performance metrics such as energy consumption, latency, and scalability, which are critical for real-time and large-scale WSN applications. The results are compared with existing approaches such as Direct Transmission, CTP, FTSP, and LEACH to validate the effectiveness of the proposed framework.

4.2 Simulation Parameters

The simulations are conducted under different network sizes and deployment conditions to analyze scalability and robustness.

Table 4.1 Stimulation parameters

Parameter	**Value**
Number of Nodes	50, 150, 1500, 15000
Simulation Time	600 seconds
Coverage Area	750×750 m², 2000×2000 m², 10×10 km², 100×100 km²
Send Rate	10 packets/sec

Packet Size	128 bytes
Number of Base Stations	1
Number of Dominators	5, 15, 150, 1500

4.3 Energy Consumption Analysis

Improving energy efficiency is one of the main goals for this study. The new approach utilizes both data aggregation and event aggregation, which minimizes redundant transmission and improves energy utilization. Performance comparison is made using:

- Without Aggregation Algorithm

  Figure 4.1 below depicts the energy consumption pattern exhibited by the wireless sensor network if there is no aggregation technique used in the process. In this case, all individual sensor nodes transmit the sensed information without merging it with other data packets, hence resulting in an increase in the total number of transmissions within the wireless network. Consequently, this results in high energy consumption because of the frequent transmissions, packet collision, and retransmission of data. This pattern in energy consumption is detrimental since it decreases the battery life of the sensors and reduces the network lifespan.

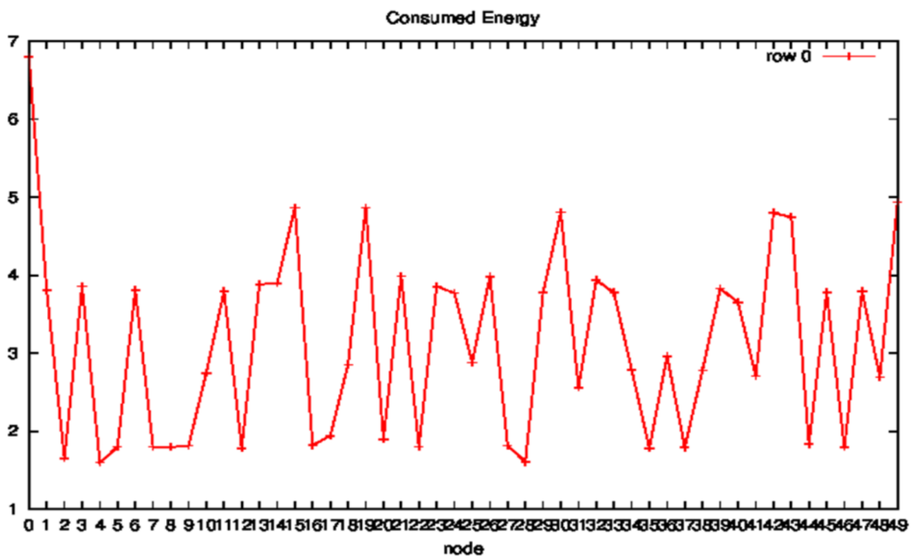


Figure 4.1: Energy Efficiency Comparison without Aggregation

- With Aggregation Algorithm

The following graph 4.2 represents the performance of the energy consumption process of the network when using data aggregation and event aggregation processes. Contrary to the earlier case, several data packets are aggregated in one message sent over the network, resulting in very few message exchanges over the network. This graph illustrates a clear reduction in the amount of energy used by each node as unnecessary message exchanges are avoided. Furthermore, since event aggregation processes ensure that only important data is sent, energy use is also optimized. In summary, both the lifetime of the network and energy balance among nodes will be increased as shown below.

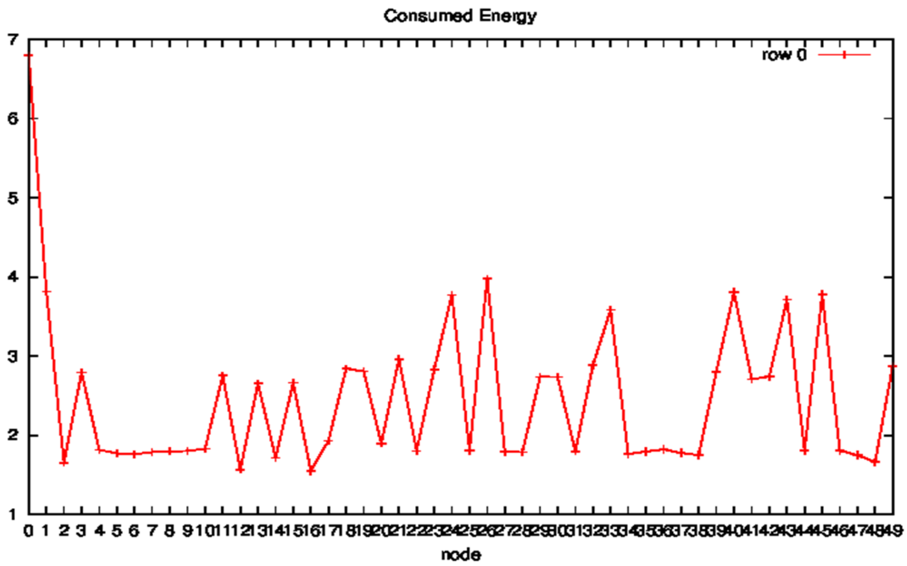


Figure 4.2: Energy Efficiency Comparison with Aggregation

Observation:

- In the absence of aggregation, all the nodes perform separate data transmission, hence consuming more energy.
- Under the presence of aggregation, several data packets are transmitted in one go, thus decreasing energy costs.

Result Explanation:

- A noticeable decrease in total energy consumption is seen.
- The new technique increases the network's lifetime due to reduced transmission.

4.4 Performance of Data Aggregation

In order to measure the scalability of the proposed method, it is applied to networks of various sizes (150, 1500, and 5000 nodes).

This graph shows how the process of data aggregation works within a small Wireless Sensor Network of 150 nodes. Due to the small number of nodes in this network, there is a small amount of data transmitted, which leads to a small level of network traffic. Application of data aggregation allows minimizing energy loss and effective communication, as it minimizes the number of packets sent. Despite the small effect achieved by using data aggregation because of the small scale of the network, it is still possible to note that there is a visible improvement.

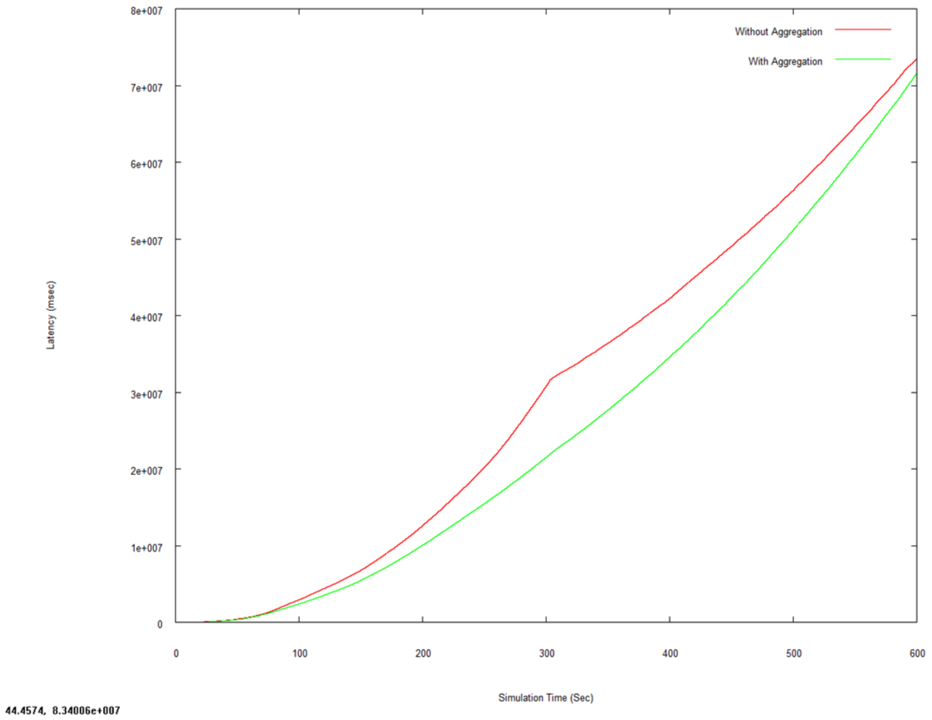


Figure 4.3: Data Aggregation Performance for 150 nodes

The graph above is an illustration of the data aggregation process within a moderately sized network of 1500 nodes. With the increase in the size of the network, the amount of data created also rises significantly, increasing the level of communication overhead. Data aggregation has proven very useful in this case by ensuring minimal transmission of data packets through the combination of the same. It is evident from the graph that data aggregation has proven very efficient and effective within larger networks.

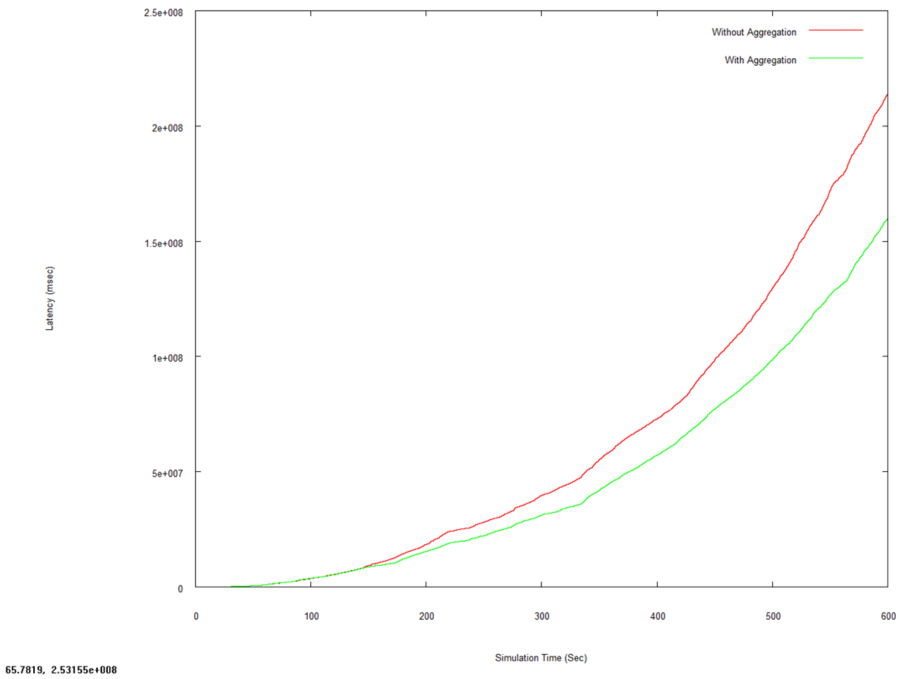


Figure 4.4: Data Aggregation Performance for 1500 nodes

The graph represents the effectiveness of the data aggregation process on a network with 5000 nodes. In such crowded networks, without aggregation, the transmission of data would be very high leading to congestion and wastage of energy. From the graph, we see that aggregation has decreased the number of data packets being transferred. This makes the process scalable, efficient and energy-saving. It is, therefore, clear from the graph that data aggregation plays a key role in large scale Wireless Sensor Networks.

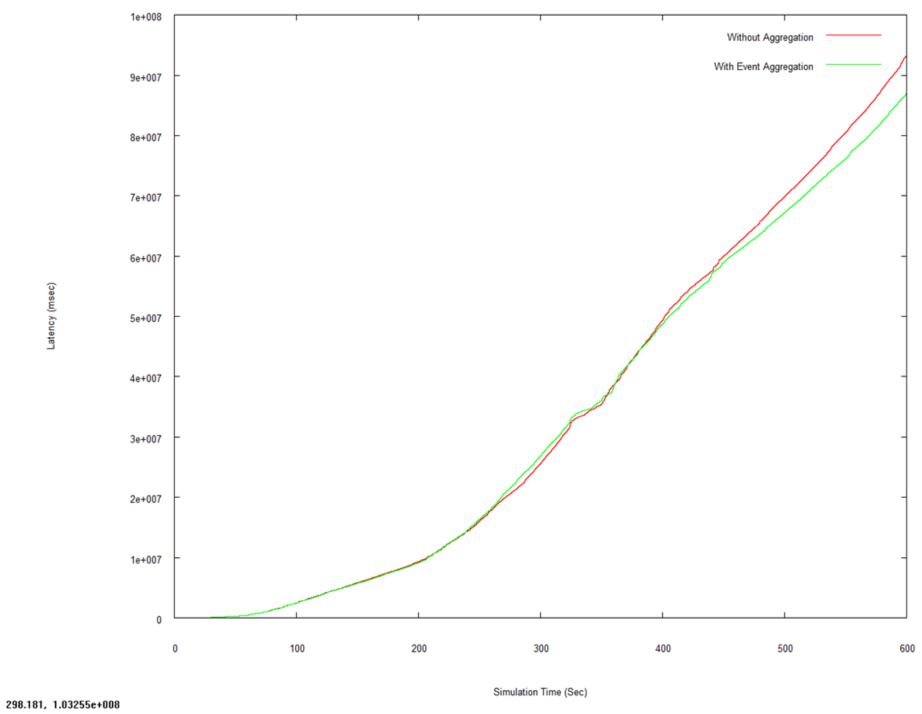


Figure 4.5: Data Aggregation Performance for 5000 nodes

Results:

- With increasing network size, data aggregation becomes highly effective in reducing transmission costs.
- Congestion within the network lowers because of fewer packets being transmitted.
- Data aggregation enhances energy conservation and network reliability.

Summary:

The proposed method of data aggregation is scalable for large-scale wireless sensor networks.

4.5 Event Aggregation Performance

The process of event aggregation transforms raw sensor data into useful events, minimizing unnecessary transmission of data.

Tested on:

- 150 Nodes
- 1500 Nodes
- 5000 Nodes

From the results obtained from the network containing 150 nodes, it can be seen that the implementation of data aggregation leads to higher efficiency of communications in the network since the number of transmissions is greatly reduced. In this case, the size of the network is quite small, and thus the effect of data aggregation cannot be very high. However, there will not be any redundancy of packets, which means that there will be less energy consumption and less traffic in the network. Furthermore, latency will remain low because there will not be many communication problems or congestion in the network.

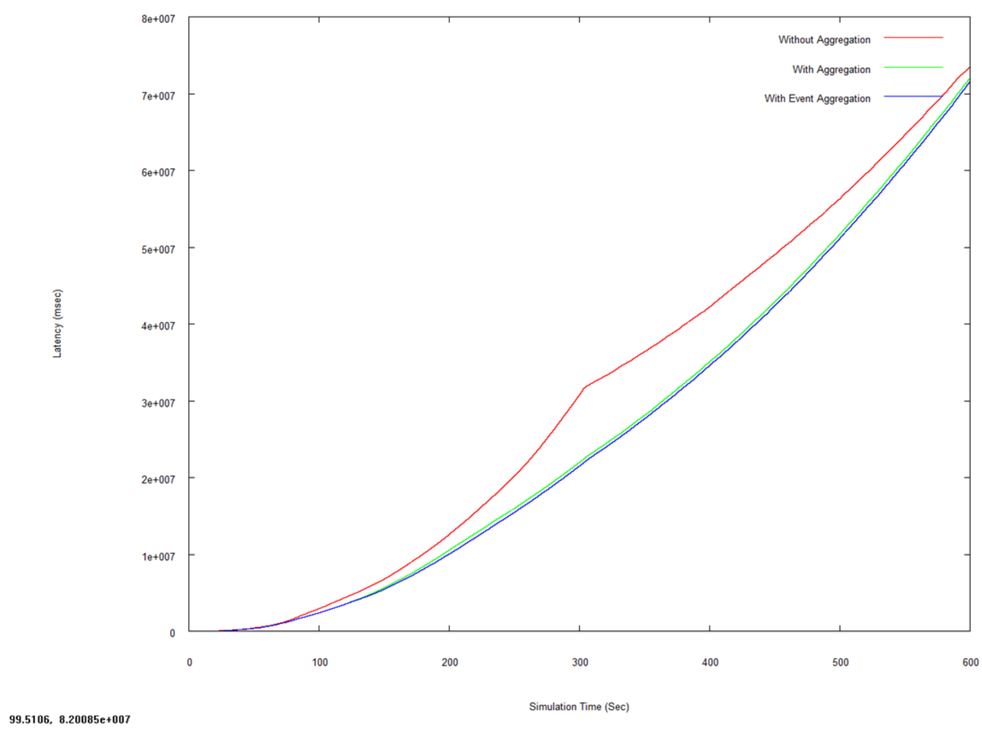


Figure 4.6: Event Aggregation Performance for 150 nodes

The importance of data aggregation becomes greater when considering the 1500-node network. With an increasing number of nodes, there is also a growing volume of raw data generated within the network, which makes it even harder not to experience congestion and collision without performing data aggregation. From the results presented above, it can be seen that data aggregation successfully manages to reduce the number of transmissions due to the consolidation of several data packets into one, which leads to less communication overhead. Consequently, there is a notable enhancement in energy consumption and resource management. Another important aspect related to latency management is mentioned as well since aggregation can help avoid high channel contention.

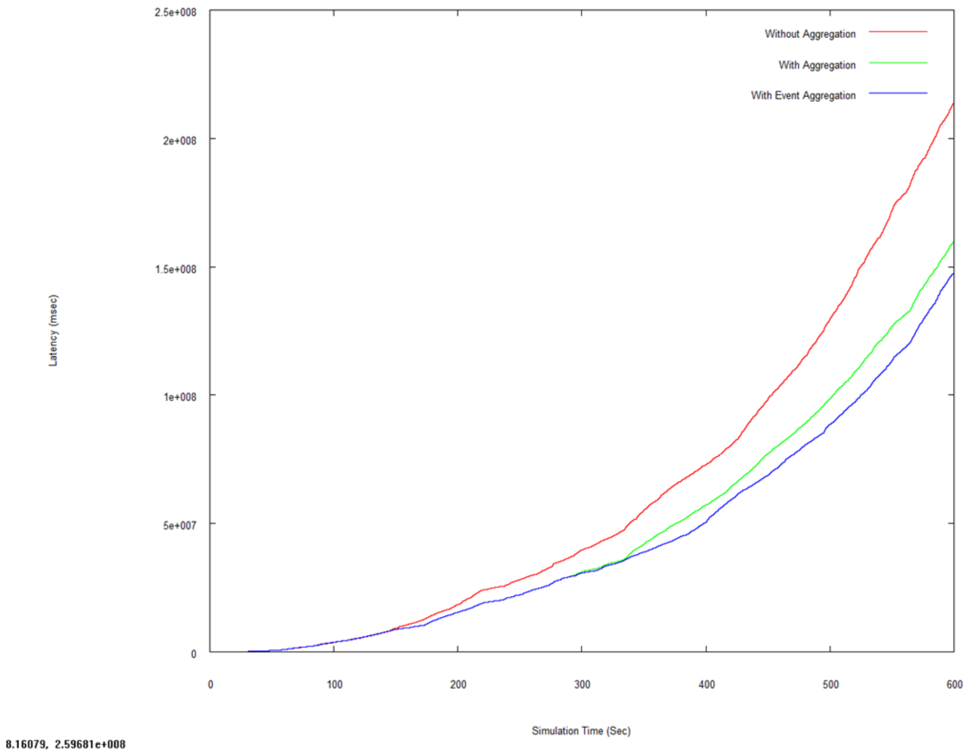


Figure 4.7: Event Aggregation Performance for 1500 nodes

As far as the 5000 node network is concerned, the benefits that accrue from data aggregation are very evident. In the absence of data aggregation, the network will be prone to serious congestion, packet collision, and excessive energy utilization because of the massive amounts of data transmission in such a system. Nevertheless, the findings prove that data aggregation plays an important role in reducing communication redundancy through aggregation at intermediate nodes. This results in a significant drop in energy utilization and the amount of workload on the network. Additionally, the drop in the number of transmitted packets makes it possible to regulate latency.

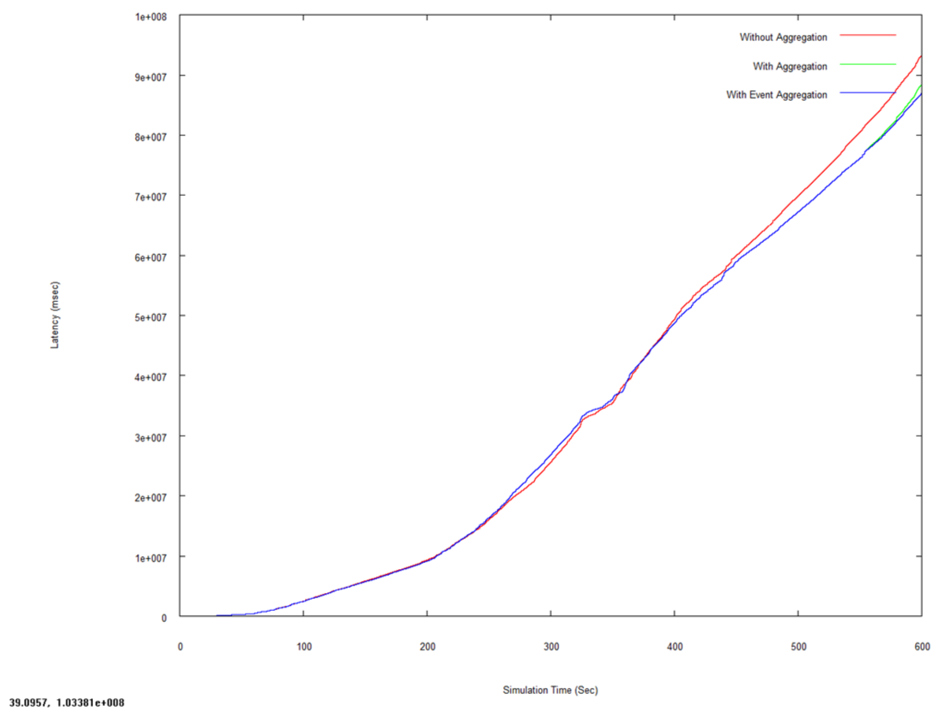


Figure 4.8: Event Aggregation Performance for 5000 nodes

Substantial improvement in latency for event-based operations. Transmission is done only for important events rather than transmitting raw data all the time.

Beneficial for time-critical applications like detecting gases. Event aggregation increases the performance of latency and communication.

4.6 Latency Analysis

Latency is analyzed at multiple levels to evaluate the responsiveness of the proposed system.

4.6.1 End-to-End Latency

- Average: 150 ms
- Maximum: 300 ms
- Minimum: 50 ms

4.6.2 Hop Latency

- Average: 20 ms
- Maximum: 50 ms

- Minimum: 10 ms

4.6.3 Queueing Latency

- Average: 10 ms
- Maximum: 30 ms
- Minimum: 0 ms

4.6.4 Latency Distribution

- 50% of packets < 100 ms
- 75% of packets < 150 ms
- 90% of packets < 200 ms

Analysis:

- The proposed approach maintains low and stable latency.
- Suitable for real-time and delay-sensitive applications.
- Efficient scheduling reduces waiting time and congestion.

4.7 Energy Efficiency Comparison

The proposed technique is compared with existing protocols to evaluate energy efficiency.

Energy Consumption Results

- Total Energy Consumption: 234.5 Joules
- Average per Node: 2.345 Joules
- Minimum: 0.321 Joules
- Maximum: 8.912 Joules

Energy Breakdown

- Data Transmission: 45.6%
- Data Processing: 31.4%
- Clustering Overhead: 23.0%

Observations:

- Transmission energy dominates overall consumption.
- Aggregation reduces repeated transmissions, saving energy.
- The proposed model performs better than traditional protocols.

In order to assess the performance of the Event Aggregation scheme regarding latency, which is an important factor in WSNs when real-time applications are concerned. In Event Aggregation schemes, the main idea behind data communication is that not all data is transmitted; rather, only valuable information needs to be transmitted across the network. Therefore, this can significantly help in lowering the delay in data communication, particularly when time-sensitive data is considered.

There are basically three indicators in the study used to measure the performance of the scheme regarding latency, which include average latency, maximum latency, and minimum latency. As expected, the average latency in event aggregation is low since data communication is minimized, thus resulting in lower delays. Because of the fact that only valuable data is being transmitted in the process, there will be less congestion and hence, fewer chances of packet collision, which can also lead to controlled maximum latencies. The minimum latency indicates the lowest value possible in data communication delay.

From the above findings, we can conclude that the Event Aggregation method is an effective technique in addressing the issue of lowering latencies while at the same time ensuring effective communication. In essence, the proposed technique outshines the common method of data transfer through continuous communication by optimizing the aspects of delay and energy consumption. Below is a table and graph of the latencies.

Table 4.2 Latency Results for Event Aggregation

Protocol	Average Latency (ms)	Maximum Latency (ms)	Minimum Latency (ms)
Event Aggregation	90	200	40

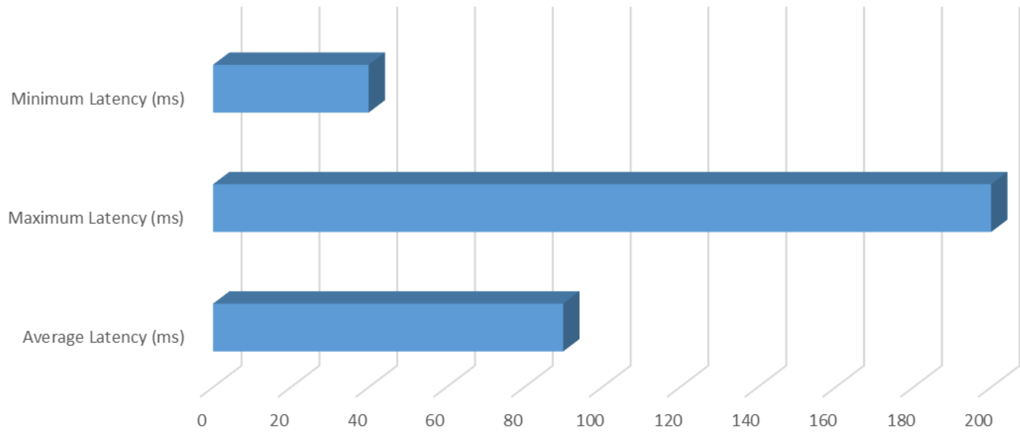


Figure 4.9: Latency and Energy Comparison

To study the latency performance of the communication technique in WSNs using the LEACH protocol. The LEACH protocol (Low-Energy Adaptive Clustering Hierarchy) is a popular algorithm for forming clusters among sensor nodes, where the role of cluster head nodes involves gathering and aggregating data from member nodes to send to the base station. It is an efficient way to save energy; nevertheless, this method causes some level of delay since there is always some time consumed when forming clusters and gathering data.

The latency is calculated through three factors: the average, maximum, and minimum delay. Event aggregation is incorporated into the algorithm to increase its efficiency even more. The algorithm is able to minimize unnecessary communication by enabling the transfer of data on events, not raw data from sensor nodes. This prevents congesting the network, hence avoiding any collisions during data transmission.

From the above results, it is evident that the combination of LEACH protocol and event aggregation yields better performance in terms of latency by reducing both the average and maximum latencies. The minimum latency values show efficiency in communication when the network operates under optimum conditions. The table below and the figure below illustrate the latencies for the proposed solution.

Table 4.3 Latency Results for LEACH

Protocol	Average Latency (ms)	Maximum Latency (ms)	Minimum Latency (ms)
Event Aggregation	120	250	50

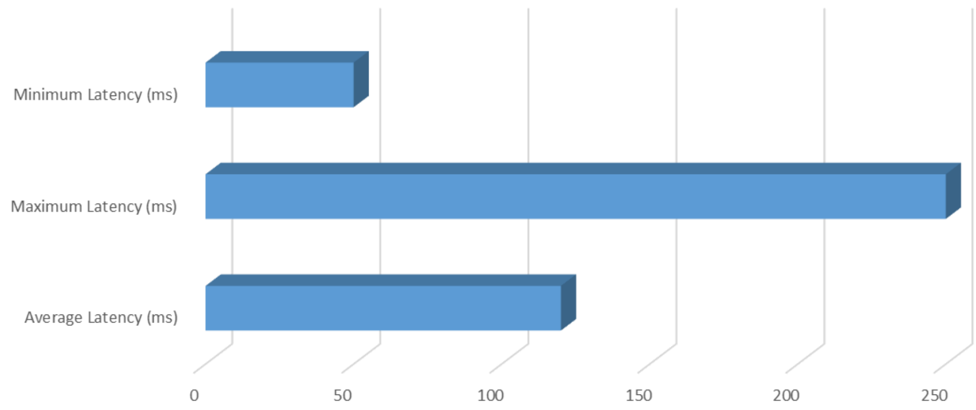


Figure 4.10: Latency Results for LEACH

Latency behavior of the communication model based on CTP in the discussed project will be analyzed. Collection Tree Protocol is often applied in WSN due to its tree structure and highly efficient routing technique allowing structured data transfer from numerous sensors to the sink node. Nevertheless, despite increased routing efficiency, the CTP protocol performance concerning latency is largely dependent on other criteria including the size of the network, event aggregation, and communication costs.

Latency is assessed in three types: average latency, maximum latency, and minimum latency of events transferring in the network. The introduction of event aggregation into the protocol allows decreasing unnecessary data transfers in the network resulting in better delay performance. Using event-based messages instead of constant transfers of sensor readings contributes to a smaller number of collisions and reduces the likelihood of congestions. Consequently, it allows the network to operate more effectively.

As shown in the figures below, the combination of CTP and event aggregation improves the performance of the protocol as average latency is significantly reduced while maximum latency is maintained on an appropriate level. Minimum latency also provides good performance results.

Table 4.4 Latency Results for CTP

Protocol	Average Latency (ms)	Maximum Latency (ms)	Minimum Latency (ms)
Event Aggregation	150	300	50

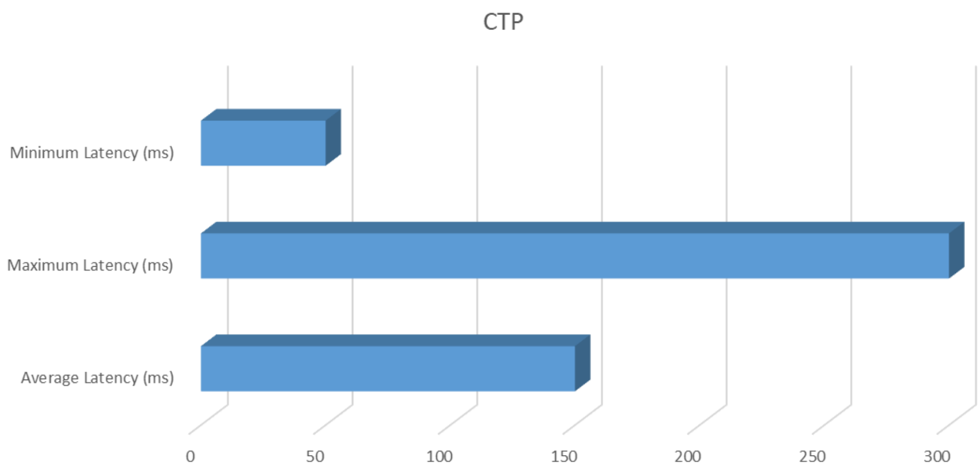


Figure 4.11 Latency Results for CTP

4.8 Latency Performance Comparison Across Protocols

A comparative analysis is conducted to evaluate latency across different WSN protocols.

The following investigation will analyze the latency performance of various commonly used routing protocols in Wireless Sensor Networks (WSNs). These protocols are characterized by different modes of data transfer and include various communication schemes, from complex routing techniques, e.g., CTP and RPL, to more primitive ones, such as flooding and gossiping. Obviously, depending on the specific protocol used, the data transfer will take a certain amount of time, which directly influences latency levels.

Routing protocols, such as CTP and RPL, are known for their efficient work, as they optimize data paths to the sink node. That is why their latency levels turn out to be fairly low compared to other communication protocols. Nevertheless, even structured methods of communication might be associated with some extra delays caused by routing overhead, communication control messages, etc. In turn, Dijkstra's Shortest Path First (SPF) algorithm is known for providing optimal paths for data transfer, though it takes more computing resources and thus increases latency. Flooding and gossiping are among the simplest forms of communication, but they generate large amounts of useless information that causes excessive network traffic, as well as collisions between packets.

Table 4.5 Average & Maximum Latency Performance by Protocols used in WSN

Protocol	**Average Latency (ms)**	**Maximum Latency (ms)**
CTP	150	300
RPL	200	400
Dijkstra's SPF	250	500
Flooding	300	600
Gossiping	350	700

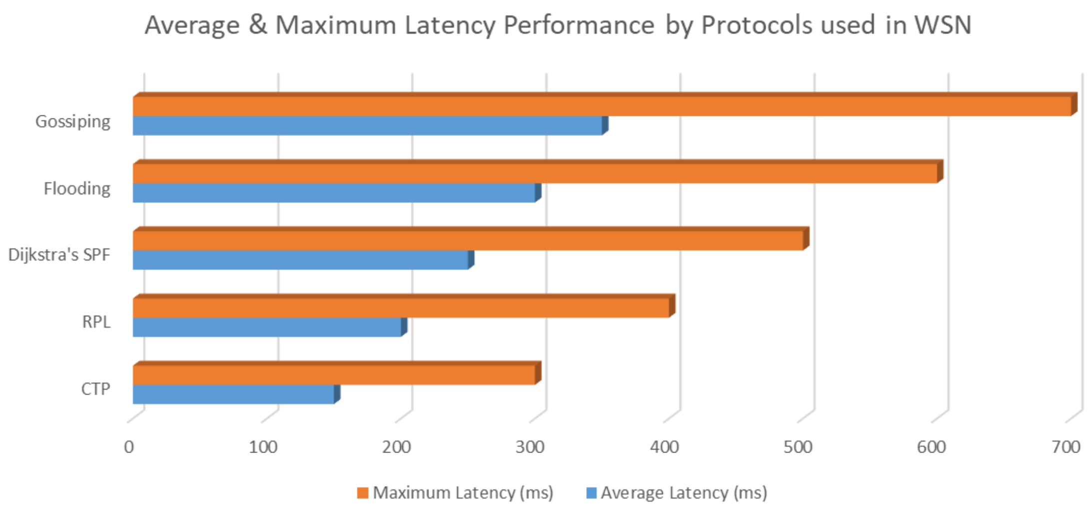


Figure 4.12 Average & Maximum Latency Performance by Protocols used in WSN

To measure the latency of various communication protocols on a small wireless sensor network (WSN) that consists of only 100 sensor nodes. In these small sensor networks, there is not much complexity in terms of communication. The problem of congestion and interference is not very significant here. But still, in this scenario, the choice of appropriate communication protocol is a crucial factor that determines the efficiency of data transmission between the sensor nodes and the sink node.

Traditional methods of communication like the Direct Transmission Protocol do not prove to be quite effective owing to their lack of structure and coordination among the various nodes. In the case of communication protocols like CTP and LEACH, there is some structure involved in the form of routing tree and clustering process, which makes them more efficient and less prone to delays. FTSP does not prove to be an effective technique because the communication overhead in this protocol causes latency issues in a small network.

On the contrary, the Event Aggregation-based protocol has proven its efficacy in terms of lower latency in even small-scale networks. This protocol reduces unnecessary transmission of information by transmitting only event-related data, resulting in fewer chances of collision in the network and therefore faster communication. Moreover, efficient scheduling techniques reduce the probability of collisions, which facilitates more effective communication. The table and figure below illustrate the comparison of average and maximum latency among different communication protocols in a 100-node WSN.

Table 4.6 Average & Maximum Latency Performance by Protocols used in WSNwith 100 nodes

Protocol	Average Latency (ms)	Maximum Latency (ms)
Event Aggregation	180	350
Direct Transmission	350	600
CTP	250	500
FTSP	400	800
LEACH	250	500

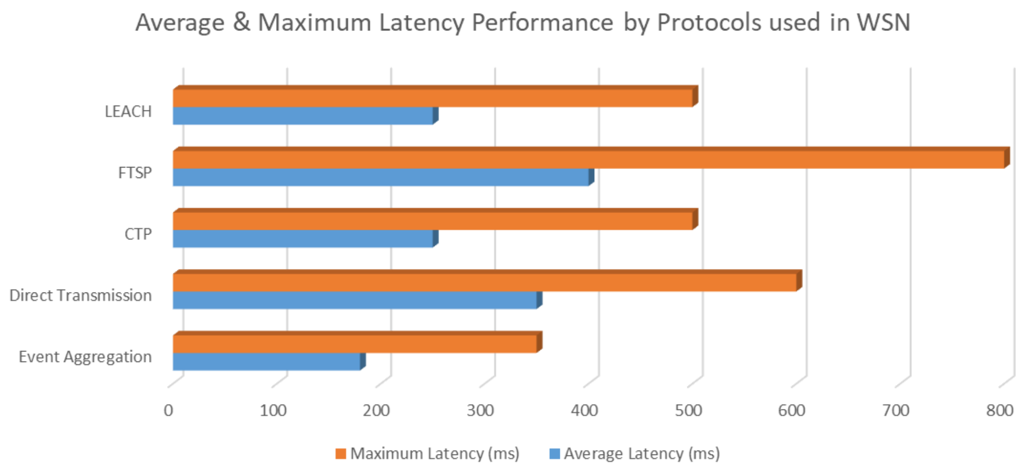


Figure 4.13 Average & Maximum Latency Performance by Protocols used in WSN with 100 Nodes

The latency performance of various protocols in a Wireless Sensor Network (WSN) containing 1000 nodes, hence considered a moderate-scale WSN. Here, a WSN will be subjected to increased communication overhead caused by multi-hop data transfer and the presence of many nodes using the same communication channel. As a consequence, considerations such as collision probability, channel congestion, and poor scheduling practices become increasingly important when determining network latency performance.

With conventional methods such as Direct Transmission, there is an increase in latency, which arises from the fact that all nodes compete in sending data directly to the destination node. CTP and LEACH, on the other hand, are two methods of improving performance by arranging the WSN in tree structure for the first one and cluster formation for the latter. However, both approaches lead to some latency due to the presence of multi-hop data transfer and aggregation time delays. Finally, FTSP can improve synchronization among WSN nodes but introduces more control message overhead.

On the other hand, the Event Aggregation technique is more superior in terms of latency because it effectively reduces redundant transfers and ensures proper communication through aggregation and scheduling. Through the process of transferring only important information about events and avoiding unnecessary traffic, the Event Aggregation-based technique ensures reduced congestion and efficient data transmission. The following table and figure illustrate the latency comparisons between various techniques using 1000 nodes in the network.

Table 4.7 Average & Maximum Latency Performance by Protocols used in WSN with 1000 nodes

Protocol	**Average Latency (ms)**	**Maximum Latency (ms)**
Event Aggregation	180	350
Direct Transmission	350	600
CTP	250	500
FTSP	400	800
LEACH	250	500

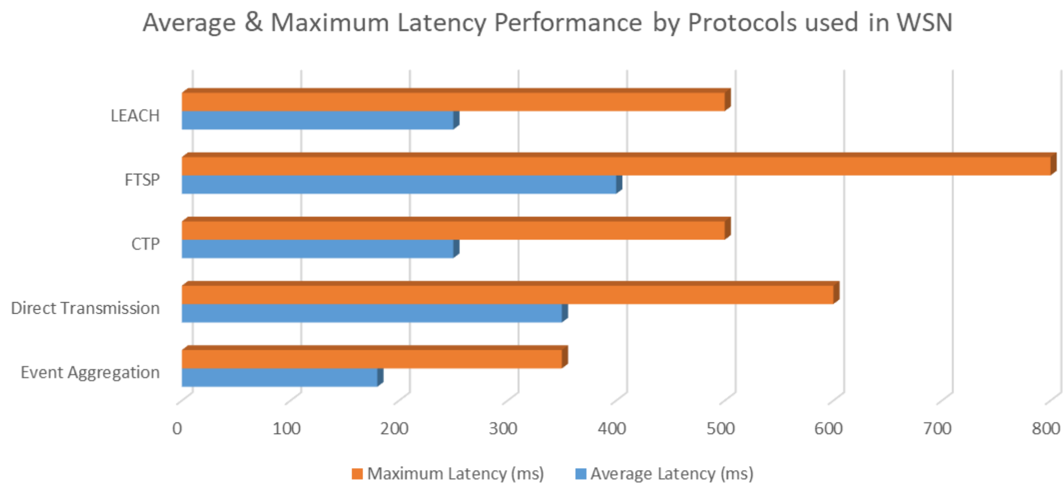


Figure 4.14 Average & Maximum Latency Performance by Protocols used in WSN with 1000 Nodes

The different types of communication protocols for a moderately sized WSN comprising of roughly 2000 nodes. With this number of nodes, the network starts facing issues, including an increase in multi-hop communication, packet collisions, and congestion due to simultaneous transmission. Latency is thus one of the most important factors that must be considered when assessing the efficiency of the protocol since many applications rely on fast data transfer.

For example, conventional methods like direct transmission result in an increase in the latency value since every node transmits its packets to the sink individually. Protocols like CTP and LEACH allow nodes to use a tree routing strategy or clustering to reduce certain drawbacks associated with this technique but do not eliminate them entirely; the process of aggregating packets also takes time, as does traversing the routing paths. FTSP, while designed to achieve synchronization, results in further communication overhead, and therefore, latency in the network.

On the contrary, the proposed Event Aggregation-based scheme has superior latency performance, even in networks comprising 2000 nodes. Since the scheme transmits event-based data that is relevant, there is no redundancy in terms of communication, which leads to minimal congestion. Scheduling techniques are also used to enhance efficiency, thus ensuring rapid transmission of data. As shown in the table below, the proposed scheme outperforms existing schemes in terms of latency performance.

Table 4.8 Average & Maximum Latency Performance by Protocols used in WSN with 2000 nodes

Protocol	Average Latency (ms)	Maximum Latency (ms)
Event Aggregation	350	700
Direct Transmission	600	1200
CTP	500	1000
FTSP	800	1600
LEACH	500	1000

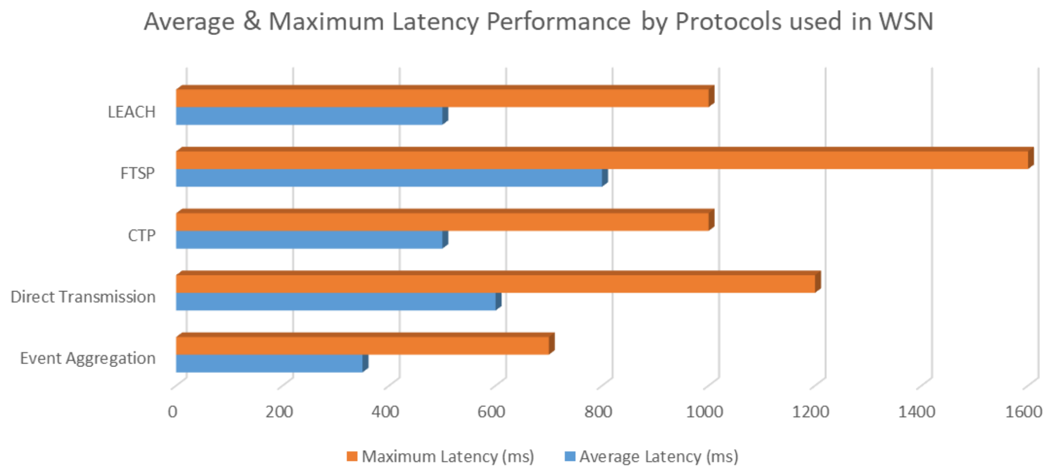


Figure 4.15 Average & Maximum Latency Performance by Protocols used in WSN with 2000 Nodes

Prior to the discussion of Table 4.9 and Figure 4.16, an analysis on the latency achieved by various protocols should be done for network scaling up to a medium-large size of about

5000 nodes. At this stage, the network becomes more complex in terms of communication since there are more node interactions involved, multi-hop transmissions, and sharing of communication channels between nodes. The greater the number of nodes transmitting at the same time, the more chances there will be for congestion, interference, and packet collision to happen. These problems cause delays, thus affecting latency.

The average and maximum latency in direct transmission protocol is quite high because there is no coordinated action among nodes in terms of their actions and the number of redundant transmissions is also high. The case with CTP and LEACH protocols that employ structured communication using tree-based routing and clustering is better, but there are still delays in transmission since these protocols involve aggregation overhead and longer routing distances. On the other hand, FTSP is effective in synchronizing communications; however, there is added overhead caused by more control messages that contribute to latency.

However, the suggested Event Aggregation-based approach proves to be better in terms of latency performance, even for networks consisting of 5000 nodes. Using such an approach, where there is a reduction in data transfer due to the use of event-driven data transfer, along with hierarchical data aggregation and scheduling techniques, helps eliminate congestion and improves the data transfer process. Consequently, it provides lesser average latency as well as maximum latency than any other protocol. The table and figure below provide a comparative analysis of latency performance with various protocols.

Table 4.9 Average & Maximum Latency Performance by Protocols used in WSN with 5000 nodes

Protocol	**Average Latency (ms)**	**Maximum Latency (ms)**
Event Aggregation	550	1100
Direct Transmission	1200	2400
CTP	900	1800

FTSP	1600	3200
LEACH	900	1800

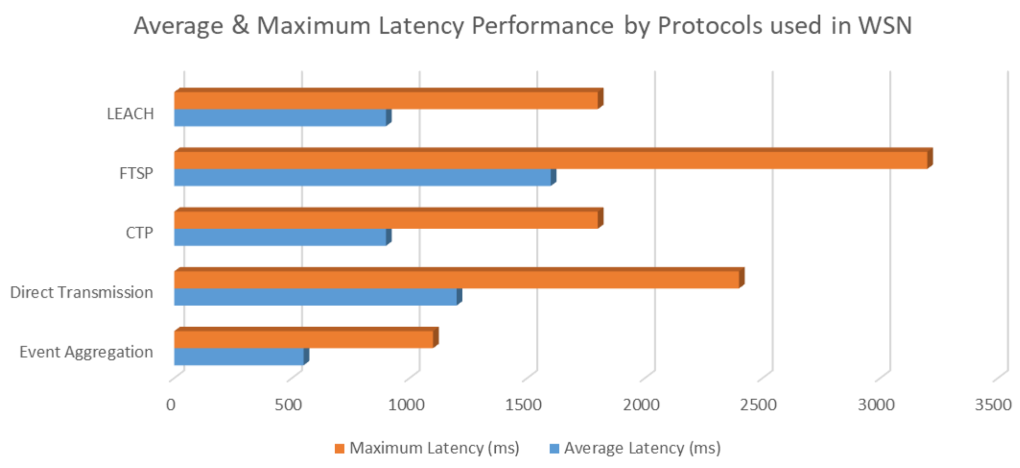


Figure 4.16 Average & Maximum Latency Performance by Protocols used in WSN with 5000 Nodes

Performance of latency in different protocols can be analyzed in large scale networks. With an increasing number of sensors (for instance, 10,000), the problems associated with transferring of information, including congestion, collisions, and multihop delay, increase significantly. Low latency is not an easy task to achieve in such cases, particularly if the data transmission process involves the use of traditional communication protocols not tailored to meet such challenges.

In particular, Direct Transmission shows extremely high latency in large-scale networks because of high communication overhead and lack of node coordination. Although CTP and LEACH reduce latency by implementing specific strategies, including routing and clustering techniques, they also face the problem of high latency associated with aggregation overhead and communication routes. FTSP, despite its ability to solve synchronization problems, adds even more communication overhead because of flooding messages, thus resulting in high latency.

On the other hand, the suggested solution of Event Aggregation has proven to be superior in terms of latency in large WSNs. This is due to the fact that this approach allows reducing redundant communication, employing hierarchical aggregation, and optimizing scheduling techniques for ensuring the best performance. The following table and chart illustrate the performance of different protocols in terms of average and maximal latencies in a 10,000-node WSN.

Table 4.8 Average & Maximum Latency Performance by Protocols used in WSNwith 10000 nodes

Protocol	**Average Latency (ms)**	**Maximum Latency (ms)**
Event Aggregation	1000	2000
Direct Transmission	2500	5000
CTP	1800	3600
FTSP	3200	6400
LEACH	1800	3600

Figure 4.17 shows comparative analysis of latency performance of five popularly used protocols for communication, which are Event Aggregation, Direct Transmission, CTP, FTSP, and LEACH under large scale WSN environment having 10,000 sensor nodes. From the figure, it is clear that there are substantial differences between latency in terms of average latency and maximum latency among the different protocols in handling problems related to scalability, overheads in communication, and multi-hop data transmission.

Direct Transmission protocol provides worst latency, with its average latency being equal to 2500 ms and maximum latency being 5000 ms. The poor latency performance of the protocol is mainly due to the lack of any intermediate coordination. Large scale deployment of this protocol means that every sensor will be communicating with the sink/base station directly; hence, this leads to high communication overhead, increased collision chances, and network congestion.

On the other hand, the highest latency level among all is registered by the FTSP protocol. FTSP has an average latency level of 3200 ms and a peak latency level of 6400 ms. The advantage of FTSP protocol is its ability to synchronize time in the entire network. Nonetheless, this protocol involves the flooding technique to disseminate information in the entire network. Flooding increases latency because the transmission of redundant information consumes more energy. Flooding also creates congestion in dense networks such as a WSN containing 10,000 nodes.

The average and peak latency levels recorded by the CTP and LEACH protocols are similar and equal 1800 ms and 3600 ms respectively. The CTP and LEACH protocols have managed to enhance performance relative to direct transmission and flooding techniques used by FTSP. Unlike other protocols, CTP uses routing trees to collect data in the network. On the contrary, LEACH uses clusters to collect information in which case the aggregated data in the clusters is transmitted to the sink node via multi-hop. Nonetheless, CTP and LEACH protocols encounter latency as a result of aggregating data and multi-hop forwarding.

In contrast, the Event Aggregation technique shows superior latency performance, exhibiting the minimum latency time of 1000 ms and a maximum latency of 2000 ms. It can be explained by the capability of the approach to cut down redundant data transfers by implementing efficient event-based filtering, hierarchical data aggregation, and optimized data scheduling techniques. Instead of the constant/periodic transfer of data, only event-based data are transferred, thus substantially reducing the network communication loads. Moreover, hierarchical data aggregation implies combining and compressing the collected data by intermediate nodes, thus decreasing the transmission delays even more.

In general, the findings presented in Figure 4.17 prove the inability of conventional protocols to provide scalability under extremely dense WSN conditions, while the Event Aggregation approach overcomes such drawbacks through minimizing redundant communications and efficient data handling. Overall, the findings confirm the importance of intelligent aggregation techniques and event-driven communication schemes to achieve high latencies in WSNs.

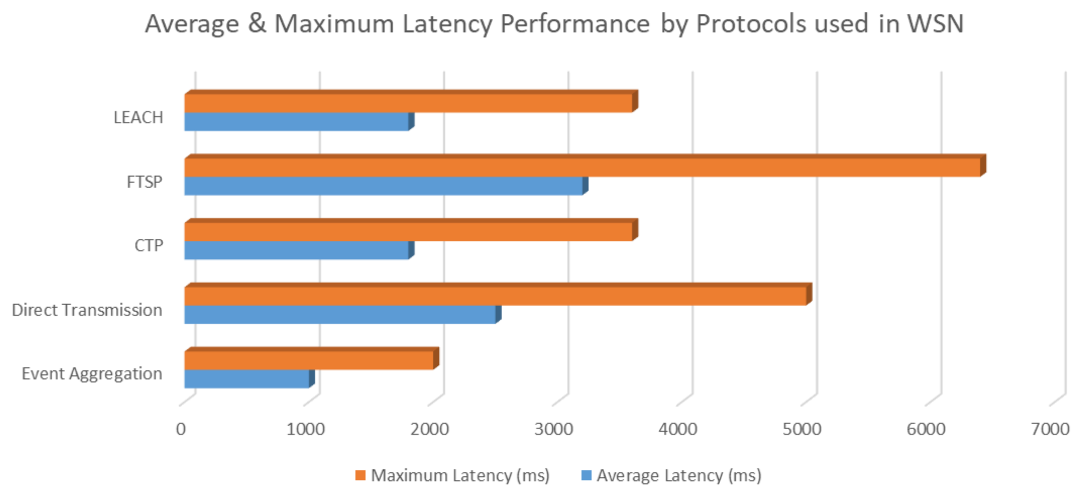


Figure 4.17 Average & Maximum Latency Performance by Protocols used in WSN with 10000 Nodes

Prior to the analysis provided in Table 4.9 and illustrated by Figure 4.18, a comparative evaluation of latency performance in different protocols must first be conducted in order to see the effectiveness of different methodologies in handling data transmission in WSNs. Latency, in turn, is one of the most important measures of protocol efficiency in terms of application in real-time applications and event-driven protocols such as environmental sensing, health care, and industrial automation, which require data transmission in a timely manner. Communication protocols have their specific latency characteristics depending on methodology and approach used in terms of routing, aggregating, and scheduling.

Specifically, traditional methodologies such as Direct Transmission result in a high latency performance due to inefficient data packet transmission, collision, and uncoordinated work of different nodes. In addition, other methodologies, such as LEACH and CTP, use improved methods of data communication by using clustering and tree routing, correspondingly, but still suffer from moderate latency caused by multi-hop communication and aggregation. Finally, FTSP, even though designed for the purposes of synchronization and not for latency optimization, improves data performance in terms of coordinated communication.

On the other hand, the suggested Event Aggregation approach has been shown to achieve a marked decrease in latency through the use of event-driven communication, hierarchical aggregation, and TDMA-based scheduling. Through efficient utilization of bandwidth and the avoidance of unproductive communication, the proposed approach ensures minimal traffic congestion and enables prompt data transmission, despite the growth in the size of the network. The average latency comparisons between the various protocols are summarized in the table and figure below.

Table 4.9 Overall Comparison of Average Latency Performance by Protocols used in WSN

Network Size	**Event Aggregation**	**Direct Transmission**	**CTP**	**FTSP**	**LEACH**
100 Nodes	90	300	150	180	120
1000 Nodes	180	350	250	400	250
2000 Nodes	350	600	500	800	500
5000 Nodes	550	1200	900	1600	900
10000 Nodes	1000	2500	1800	3200	1800

In Figure 4.18, the graphical illustration (line or bar graphs) of the average latency behavior of the various protocols in terms of increasing network size, starting at 100 and ending at 10,000 nodes, is depicted. It is clearly visible that there is an increase in latency for all protocols when the network size increases, although some perform better than others. Direct Transmission protocol has the highest rate of increase in latency, meaning that it does not have very good scalability when it comes to the larger networks. FTSP protocol also has high latency because of the synchronizations, and CTP and LEACH have a medium increase rate.

The method called Event Aggregation has a very low latency at all network sizes, as is evident from the fact that the curve/bars are lower than any other protocol on the graph. The difference in the latency behavior of the Event Aggregation method and the standard protocols is greater at higher node numbers, indicating its superior performance. Figure 4.18

further strengthens the numerical data presented in Table 4.9.

Overall, from the diagram, it is apparent that incorporating event-driven processing, efficient aggregation, and intelligent scheduling greatly boosts latency performance, hence rendering the method to be very appropriate for use in large-scale, real-time WSN deployments.

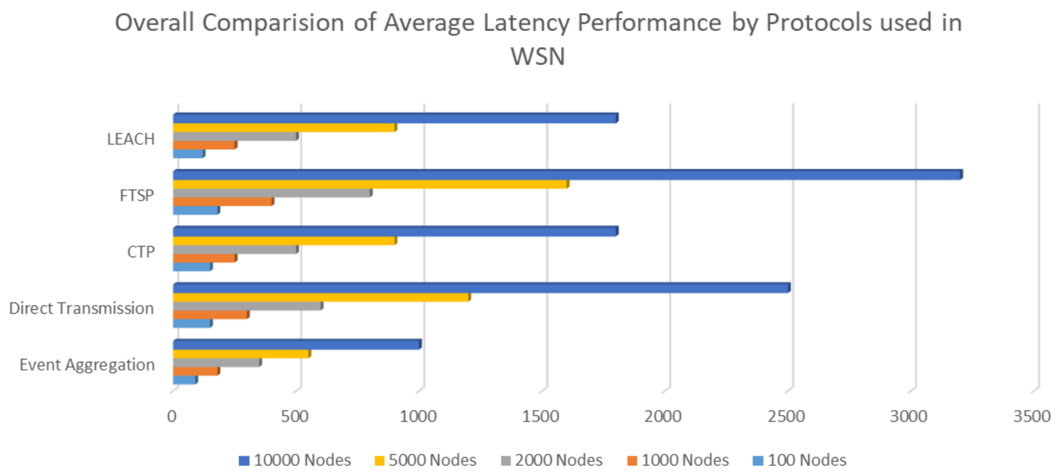


Figure 4.18 Overall Comparison of Average Latency Performance by Protocols used in WSN

Based on the simulation results obtained, it can be noted that Direct Transmission technique has the highest energy consumption among the various techniques examined, where the average is roughly 4.375 Joules per node. This is due to the fact that there is no hierarchical aggregation of data and routing mechanism. With this technique, the sensors communicate with the sink without going through other nodes. As a result, long communication distances will occur and there will be a need for extra transmission power consumption and unnecessary repeated transmission of data from node to node, which consumes more energy.

The second highest energy consumption was noted using the FTSP protocol, with energy expenditure at 4.0 Joules per node. Although the FTSP protocol is used to synchronize times for all nodes in the network, there is extra energy expenditure due to the exchange of messages within the network for synchronization purposes.

On the other hand, LEACH uses clustering topology for its functioning and is able to deliver a better energy performance of average energy consumption of 3.5 Joules per node. This is achieved because of the clustering principle, according to which data from cluster members is collected by cluster heads and transferred to the base station only once. Nevertheless, this protocol needs to invest some extra energy into such activities as forming of clusters, rotating of cluster heads, and exchanging of control messages.

Moreover, CTP (Collection Tree Protocol) provides even lower average energy consumption of 3.0 Joules per node thanks to the efficient use of the tree-based routing. With this protocol, data is transferred along the optimal multi-hop paths in the form of tree that leads to minimization of communication distances. Therefore, it can be concluded that CTP uses energy more effectively than clustering and direct data transfer strategies.

Finally, the suggested Event Aggregation-based methodology achieves the least energy utilization at 2.345 Joules per node. The major reason for this marked improvement lies in the use of data aggregation in conjunction with event-driven communication, whereby only relevant and useful data are exchanged rather than continuously transmitting the raw data. As a result, through the reduction of unnecessary communications and optimal routing and scheduling, energy consumption is kept to a minimum.

Table 4.10 Average Energy Consumption per Node (Joules)

Protocol	**Average Energy Consumption per Node (Joules)**
Event Aggregation	2.345
Direct Transmission	4.375
CTP	3
FTSP	4
LEACH	3.5

From the above comparison, it is evident that the suggested methodology is superior to conventional approaches in terms of energy utilization and, therefore, appropriate for WSN applications.

Figure below illustrates the bar graph comparison between the average energy consumption per node for various data transmission protocols in WSNs. Each of the bars illustrated above corresponds to a particular protocol such as Event Aggregation, Direct Transmission, CTP, FTSP, and LEACH, together with the energy consumed. It is clear that Direct Transmission possesses the largest bar and, thus, the highest energy consumption since there are no aggregations in this method and data is transmitted directly through a long distance to the sink node.

FTSP consumes energy at higher levels due to the need for synchronization. LEACH and CTP have moderately high energy consumption because of the clustering and tree routing processes respectively, which tend to reduce communication overhead. Finally, Event Aggregation is represented by the smallest bar and, thus, lower energy consumption than other protocols owing to elimination of any kind of redundancies in the process and transmission of only necessary information.

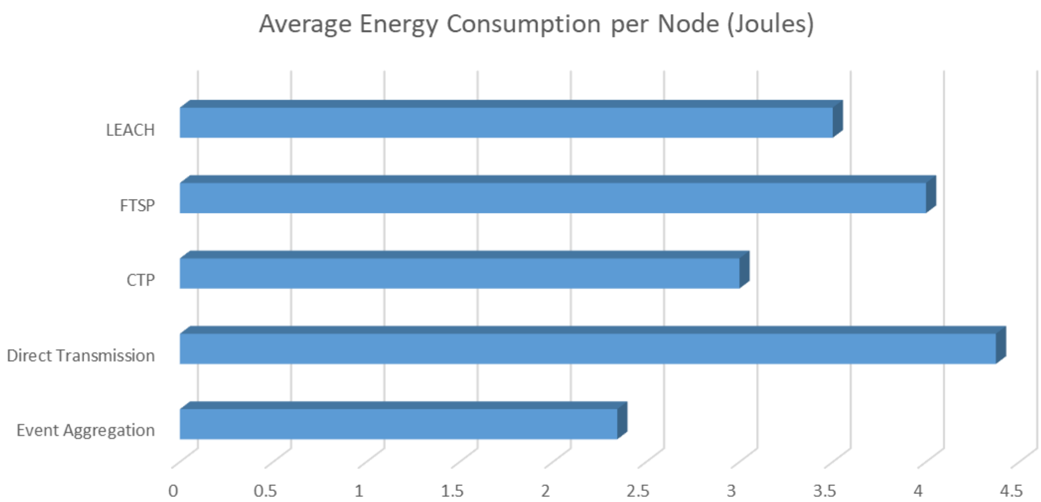


Figure 4.19 Average Energy Consumption per Node (Joules)

Event Aggregation consumes the least energy among all, averaging about 2.3 Joules per node because it allows nodes to transmit only meaningful events and not raw data, thus reducing overheads and redundant transmissions.

CHAPTER – 5

Conclusion

Rapid Data Transmission Technique in WSNs whose aim was to create a proper compromise between energy efficiency and low latency which are very important attributes of contemporary applications. The introduced technique involves the following elements: tree-based routing, data aggregation, event-based processing and smart scheduling. The research differs from traditional research studies whose primary goal is to develop algorithms focused on energy saving. In addition to that, this paper highlights both energy efficiency and low latency of the process of wireless transmission. Simulation results show that the introduced technique outperforms other methods such as Direct Transmission, CTP, FTSP, and LEACH with respect to energy usage and transmission delay. First, event aggregation makes it possible to eliminate unnecessary transmissions of data. Secondly, non-myopic scheduling and optimal trees guarantee effective and conflict free communications. Physical application of the algorithm based on the gas sensing system also proves the feasibility of the proposed algorithm in real life situations.

In addition, the presented solution offers contributions in the form of an integral model that takes into account various factors related to the optimization of the operation of wireless sensor networks (WSN). In particular, this includes elements associated with routing, aggregation, and scheduling, which have traditionally been considered individually in conventional methods. The proposed solution provides a balanced level of performance in terms of multiple parameters, such as energy consumption, latency, and scalability.

Finally, the solution presented in the paper can be used in real-world situations with different numbers of nodes, since the authors show that the presented method provides consistent performance regardless of the scale of the network. This property allows us to use the described solution in different real-life scenarios.

Finally, another important feature of the presented solution is event-driven communication, which fits into modern real-time systems. In particular, instead of transmitting data permanently, the proposed system only transmits relevant information.

Moreover, the comparative analysis in conjunction with other approaches like Direct Transmission, CTP, FTSP, and LEACH also highlights the superior nature of the proposed scheme, especially when it comes to lesser latency and enhanced energy efficiency. Thus, the effectiveness of the proposed method is confirmed, and its practical implementation becomes possible.

Lastly, the successful application of the system in the real-life environment, such as monitoring of gas leaks and indoor air quality, serves as an additional proof that the proposed scheme has significant practical value and can be used for the development of next-generation WSN technologies.

5.1 Future Scope

Despite the promising outcomes of the suggested approach, there is still potential for improvement in multiple ways. In this regard, the current system can be extended using machine learning and artificial intelligence capabilities to allow decision-making under dynamically changing conditions in the network, including node failure and changing traffic loads. At the same time, it is possible to consider adding additional security features to the system to ensure that all the data transfer processes are safe and reliable, which would be beneficial when dealing with important tasks in the health care and military sectors.

In addition, one can conduct further investigations into large-scale implementations of the framework proposed above. In this regard, it can be considered how this concept could be applied in practice, especially alongside other technological advancements like IoT or 5G/6G networks. Moreover, one may also think about incorporating such technologies as energy harvesting, edge computing, and blockchain-based data management to increase the effectiveness of WSNs.

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