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

A SYNOPSIS

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ABSTRACT

Wireless Sensor Networks (WSNs) are now considered an integral part of any technological environment and are used for applications such as environmental monitoring, smart cities, industrial automation, and healthcare. WSNs consist of many sensor devices that operate together to collect and transmit data to a central base station. However, due to battery and processing limitations, one of the major challenges associated with WSNs is to ensure efficient data transmission with low latency and energy efficiency. One of the major research challenges that must be addressed to meet these two contradictory requirements. The purpose of this research is to present a method for quick data transmission that incorporates tree generation, data aggregation, and event aggregation to achieve the dual objectives of minimizing latency and reducing energy consumption. This research is different from other research that mainly considers energy efficiency in data transmission. This research highlights the significance of latency along with energy consumption. The proposed method for quick data transmission starts with the creation of an optimized aggregation tree that helps in structured data transmission among sensor nodes. Then, data aggregation techniques are used to transmit multiple sensor data in a single unit. Event aggregation is another technique that is used to convert sensor data into useful events for quick transmission. To improve the overall performance, the proposed framework utilizes the benefits of both centralized and distributed scheduling approaches, along with the advantages of sophisticated scheduling policies for conflict-free data transmission. The proposed framework also optimally manages the communication between the nodes by reducing the number of collisions and optimally allocating the time slots, thus improving the performance. Further, the fault tolerance aspects, such as the use of retransmission, replication, and signal quality, are also considered for improving the performance of the network in harsh and dynamic environments. The performance of the proposed approach is validated through extensive simulations using standard simulation tools such as Castalia and NS2. The simulation results show the performance improvements of the proposed approach compared to the conventional approaches, such as LEACH and CTP. The proposed approach has improved the performance parameters substantially, making it more suitable for large-scale WSN applications.

To further enhance the applicability of the research, a prototype of the framework, based on a gas sensing system, is implemented using a NodeMCU microcontroller and the MQ7 sensor. The system is capable of real-time data acquisition, transmission, and analysis via a cloud-based interface, thereby validating the applicability of the proposed framework in real-world applications. To evaluate this research, it is proposed that this research provides a comprehensive and efficient solution for rapid data transmission in WSNs using tree communication, aggregation, and scheduling. The proposed method is not only energy-efficient but also provides low-latency communication, making it highly suitable for next-generation WSNs.

1 Brief Description on the State of the Art of the Research Topic

1.1 Introduction

The potential uses of Wireless Sensor Networks (WSNs) in many areas, including industrial control systems, medical care systems, military surveillance systems, smart city systems, and environmental monitoring systems, have received considerable attention over the past few decades. Wireless sensors are generally a large number of nodes that are dispersed over a region and are capable of sensing and processing the environment. Further communication from the nodes to the base station occurs by processing the data received from the nodes. The nodes are severely constrained by the limited energy and communication resources available to them. Therefore, one of the major problems associated with WSNs is the transmission of the sensor nodes to the base station.

One of the most widely utilised communication methods in WSNs is convergecast. Sensor nodes gather data for convergecast communication and transmit it to a single node known as the base node. Multi-hop communication is the foundation of convergecast communication in its most basic form. Using this method, the base node receives messages from other sensor nodes via the sensor nodes acting as intermediary nodes. However, there are a few issues with this communication method, including energy consumption, redundant messages, and latency. Since sensor nodes are battery-powered and cannot be changed or recharged, convergecast communication in WSNs has mostly focused on increasing energy efficiency throughout the years. Various methods, such as data aggregation, have been proposed to reduce the number of messages sent in a WSN. Data aggregation combines multiple data packets and sends them in a single packet, thus improving energy efficiency. Similarly, routing protocols have been improved to reduce communication cost and optimize energy efficiency.

However, with the development of modern applications such as real-time monitoring systems, disaster management, and Internet of Things (IoT) environments, WSNs have witnessed a paradigm shift in terms of requirements. WSNs not only need to be energy-efficient, but they also need to support low-latency communication, where data needs to be sent in a rapid and efficient manner. For example, in applications such as gas leakage detection and health monitoring, delays in sending data can result in serious consequences. This is where one of the major drawbacks of existing methods is evident. Apart from the problem of latency, other problems like network congestion, collision, and scheduling also affect the performance of the conventional convergecast approaches. As the nodes are trying to transmit the data at the same time, the chances of interference are more, which results in retransmission of the data, thereby increasing the energy consumption of the nodes. Thus, the major research challenge is to achieve a balance between energy efficiency and latency optimization for the design of the next generation of WSNs. To improve the performance of the WSN, the recent research trends are focusing on the integrated approaches of tree-based structures, data aggregation, event-based processing, and intelligent scheduling approaches for the design of the next generation of WSNs. The tree-based structures help to organize the WSN in a more efficient manner, while the event-based processing improves the performance of the WSN by aggregating the raw data received from the sensors, thereby reducing the amount of data transmission over the network. The intelligent scheduling approaches help to avoid conflicts, thereby reducing the overall latency of the WSN.

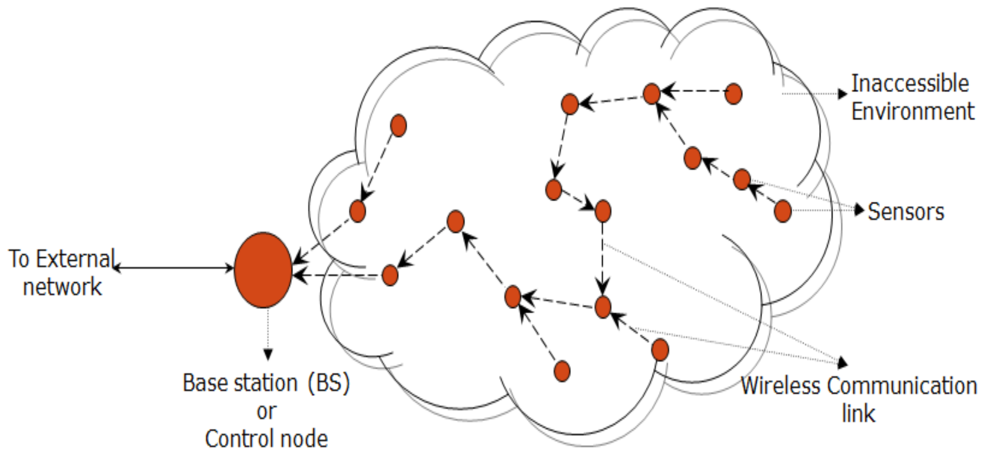


Figure 1 Basic Convergecast Communication in Wireless Sensor Networks

1.2 Literature Survey

One of the major technologies employed for data acquisition and monitoring in areas such as smart cities, industrial control systems, health monitoring systems, and environmental monitoring systems is Wireless Sensor Networks (WSNs). One of the major communication models of WSNs is convergecast, where data from multiple nodes of the wireless network is transmitted to a single node called the sink node.

1.2.1 Convergecast Problem and Challenges

The convergecast problem has mainly been concerned with the collection of data from distributed nodes while minimizing communication costs. In the past, most studies focused on energy efficiency. It was assumed that the main goal was to maximize the lifetime of the network. However, in recent times, due to the introduction of real-time and delay-sensitive applications in WSNs, such as disaster response and health monitoring, the importance of latency has also become significant.

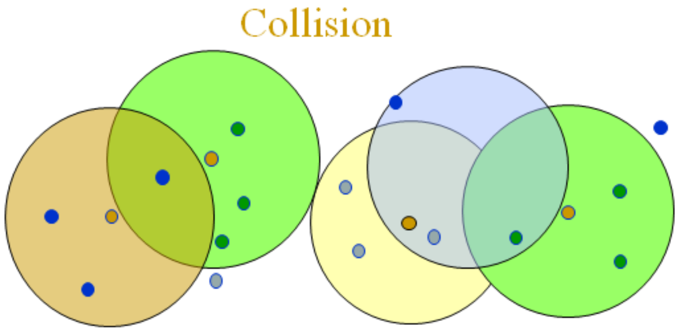


Figure 2 Collision in the Convergecast problem [1]

The main challenge in convergecast communication is the collision of packets. When multiple nodes send messages simultaneously using wireless communication media, collisions can happen. This can result in retransmission of messages and increase the delay and energy consumption of the network. In recent studies, the main goal has been to achieve a trade-off between latency and energy efficiency.

1.2.2 Distributed Convergecast Algorithms

For solving the problems of scalability and varying network conditions, distributed convergecast algorithms were introduced. In these types of methods, each node is responsible for deciding its own transmission strategy. One of the methods of distributed convergecast is as follows: The transmitting range is set to the nearest active node, Messages are transmitted with a certain probability p to avoid simultaneous transmissions, Nodes go to an inactive state after successful transmission without any collisions, Data is merged in case of collisions to avoid redundant transmissions.

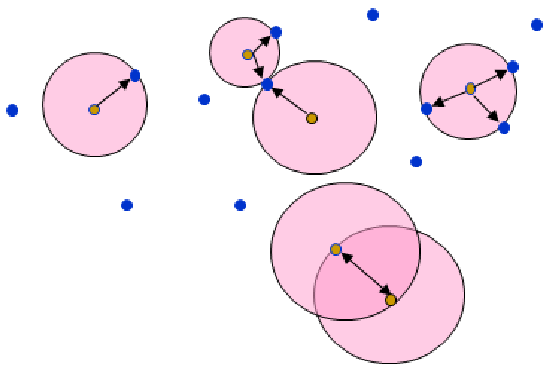


Figure 3 Distributed Convergecast Algorithm [4]

These methods reduce network congestion while keeping it energy-efficient. However, these methods can cause delays in the network.

1.2.3 Data Aggregation in WSNs

Data aggregation is one of the techniques used to enhance the performance of convergecast operations.

This technique has been widely used in the optimization of convergecast operations. In data aggregation, different data packets are aggregated and transmitted in the form of one single packet.

The advantages of using data aggregation are: It minimizes the occurrence of packet collision, It minimizes the communication overhead, It saves energy up to 70%.

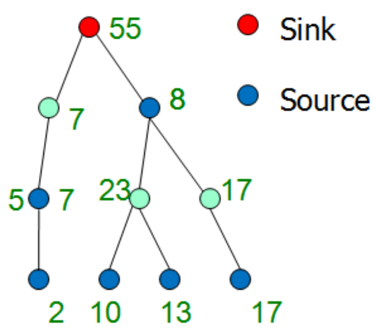


Figure 4 Data Aggregation Convergecast [5]

In addition, in-network filtering helps in the reduction of irrelevant data. However, this technique also has the disadvantage of incurring delay in the process of data aggregation due to the waiting time of the nodes.

1.2.4 Event-Based Aggregation

Event aggregation is a further extension of traditional data aggregation. It converts sensor readings into high-level semantic events. In this case, nodes do not send raw sensor readings. Instead, they send events like "threshold exceeded by temperature" and "motion detected." This technique has the advantages: Data abstraction and interpretability, Reduced communication cost by only sending relevant events, and support for both latency-constrained and energy-constrained applications. It also enables the creation of aggregation trees based on events.

1.2.5 Delay Bounded Event Aggregation (DBEA)

To meet the critical requirements of latency, the Delay Bounded Event Aggregation (DBEA) algorithm has been proposed. The DBEA algorithm helps to achieve partial aggregation, which enables the nodes to transmit the data even though the nodes are unable to achieve the required aggregation within a certain bound of delay.

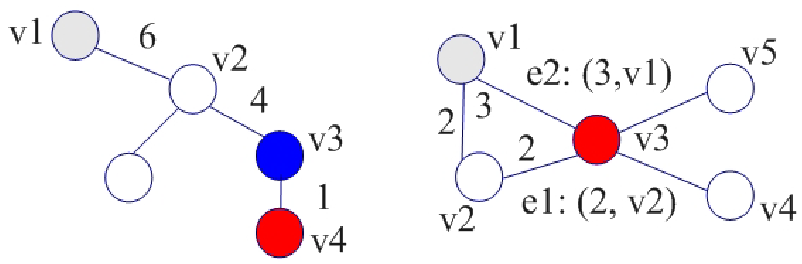


Figure 4 Delay Bounded Event Aggregation Algorithm [4]

Major characteristics of the DBEA algorithm: It meets the bound of the delay, It balances the energy efficiency and latency, It achieves 35% of the energy savings.

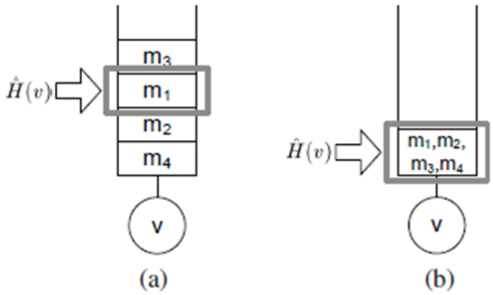


Figure 5 Delay Performance of Scheduling with Data Aggregation [6]

1.2.6 Impact of Aggregation on Delay Performance

The impact of data aggregation on the performance of the network, considering the overall delay, has already been studied in the literature. It has been observed that the overall latency of the convergecast communication is heavily affected by the impact of data aggregation.

Without In-Network Aggregation:

In the absence of in-network data aggregation, each node sends the data independently, resulting in many nodes transmitting, thereby increasing overall channel contention. As a result, the overall delay is lower bounded by a higher value.

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

With In-Network Aggregation:

In the presence of in-network data aggregation, the nodes aggregate the data received from other nodes and transmit it as a single packet, thereby reducing the overall channel contention to a greater extent. As a result, the overall delay is upper-bounded by a lower value.

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

The above analysis that the overall impact of data aggregation is quite high, which results in the efficient performance of the overall network, especially for dense wireless sensor networks.

1.2.7 Scheduling Policies for Efficient Convergecast

The scheduling policies are essential in reducing the transmission conflicts and improving the delay performance. Different scheduling policies have been proposed and are divided into two classes: myopic and non-myopic policies.

Myopic Scheduling Policies

The scheduling policies are based on the current state of the network:

- Maximum Weight Matching (MWM): This policy minimizes the incremental delay.
- Maximum Size Matching (MSM): This policy maximizes the number of nodes scheduled.
- Greedy Maximal Matching (GMM): This policy schedules the transmission using local optimization of the messages.

Non-Myopic Scheduling Policies

The policies are also based on the future state of the network:

- Non-Myopic MWM (NM-MWM): This policy extends the MWM policy.
- Non-Myopic MWM with Analysis (NM-MWM+A): This policy optimizes the scheduling and minimizes the future delays.
- Non-Myopic GMM (NM-GMM): This policy extends the GMM policy.

The non-myopic policies have better delay performance and are efficient in utilizing the network, although with increased complexity.

1.2.8 Tree-Based Data Aggregation Structures

Tree-based routing structures are very popular for efficient organization of communications in WSNs. There are different approaches to building a tree-based routing structure, which provide different trade-offs for WSN applications:

- Shortest Path Tree (SPT): It minimizes the path to the sink node, thereby reducing the overall delay.
- Collection Tree Protocol (CTP): It is a popular protocol for WSN applications.
- Minimum Interference Tree (MIT): It reduces the interference between the nodes.
- Bounded Degree Minimum Radius Spanning Tree (BDMRST): It strikes a balance between coverage and node degree.
- Degree Constrained Tree (DCT): It is used to improve the scalability of the network.

1.2.9 Centralized Data Aggregation and Scheduling

A centralized method is based on complete knowledge of the network and is used for global optimization. The basic steps for any centralized algorithm are:

Step 1: It demonstrates the process of aggregating data from the dominatees to the dominators. In our greedy strategy, the set of dominators will collect data from as many dominatees (whose data has not yet been collected by a dominator) as possible throughout each time frame.

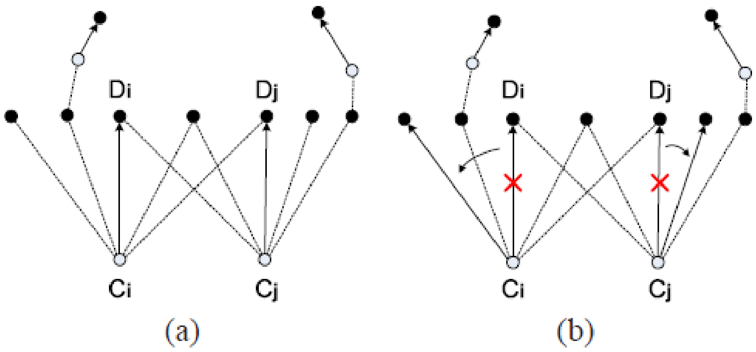


Figure 6 Greedy aggregation of data from dominatee nodes to dominators

Step 2: Reconnect any unsuccessfully linked domains. In order for these new links to communicate simultaneously, we next use step 2 to reconnect these dominatees to the dominators (and may not schedule some of the chosen dominatees in the present timeslot).

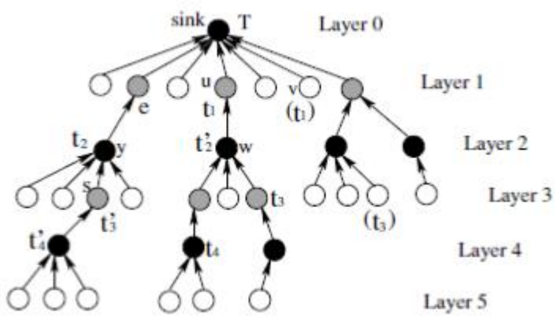


Figure 7 Reconnection of unlinked nodes to ensure connectivity.

Step 3: Construction of centralized aggregation, including: Leaf indicator, Competitor set, Ready competitor set, Transmission time slots, Number of children

Step 4: Each dominatee sends information to the nearby dominator with the lowest rank. Data is aggregated from lower-level dominators to higher-level dominators, and ultimately to the network's topology center at the base of the aggregation tree. The topology canter then uses the shortest path to send the combined data to the original sink. Based on the analysis of performance:

- Without aggregation: High latency due to multiple transmissions.
- With aggregation: Significant reduction in delay due to aggregation.

Upper and lower bounds for latency:

- Upper bound: $16R+\Delta-14$
- Lower bound: $4R+\Delta-3$

where R is the radius of the network.

1.2.9 Simulation Tools for Performance Evaluation

To ensure that the new algorithms and protocols that have been proposed can be implemented effectively in WSNs, several simulation tools can be used. These include:

- NS (Network Simulator): This is a general-purpose network simulator.
- TOSSIM: This is a simulator that has been tailored for TinyOS-based WSNs.
- SensorSim: This is a sensor network simulator that has been developed by extending NS.
- Atemu: This is a sensor node emulator.
- Avrora: This is a cycle-accurate simulator that can be used for simulating embedded systems.
- Castalia: This is a simulator that has been tailored for simulating wireless channel and node behavior.

These tools facilitate comprehensive evaluation of latency, energy consumption, scalability, and reliability. To analyze the effectiveness of data aggregation and scheduling strategies, simulations were conducted under different node densities and deployment areas.

1.2.9.1 Simulation Result of 16 Nodes in 60 × 60 m²

This simulation represents a small-scale network with 16 sensor nodes deployed in a 60 × 60 m² area. The graph illustrates the energy consumed per node.

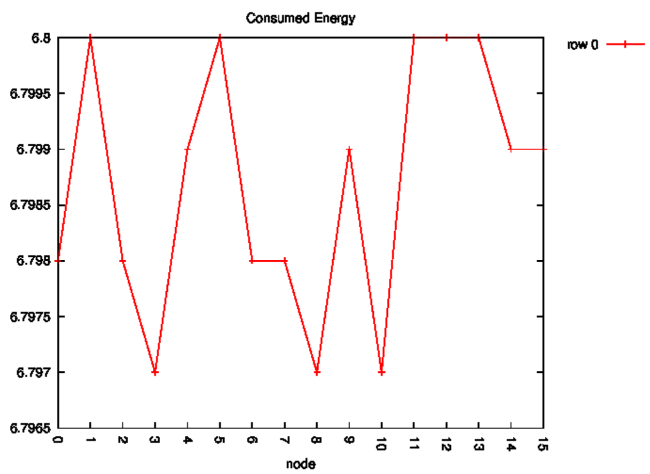


Figure 8 Simulation Result of 16 nodes in 60x60 meters.

1.2.9.2 Simulation Result of 150 Nodes in 1500 × 1500 m²

This scenario involves a high-scale network deployment where there are 150 nodes over a 1500 x 1500 m² area.

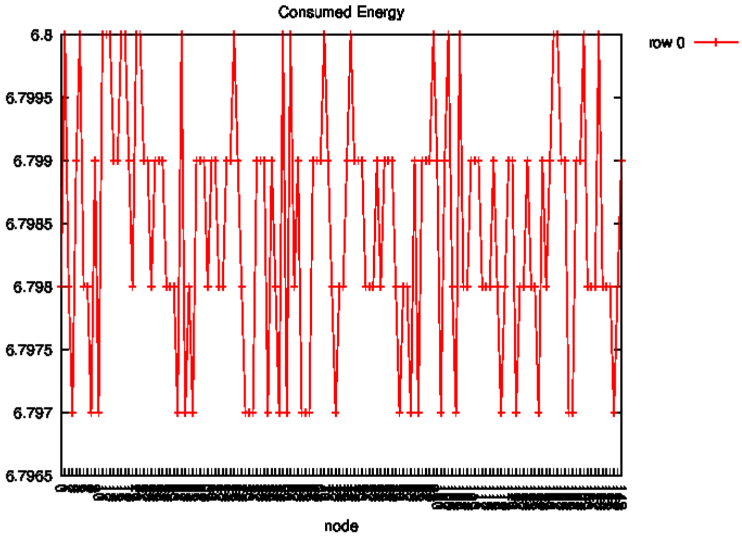


Figure 9 Simulation Result of 150 nodes in 1500x1500 meters

1.2.9.3 Simulation Result of 50 Nodes in 100 × 100 m²

This simulation is for a medium-scale network, with 50 nodes distributed in a 100 x 100 m² area.

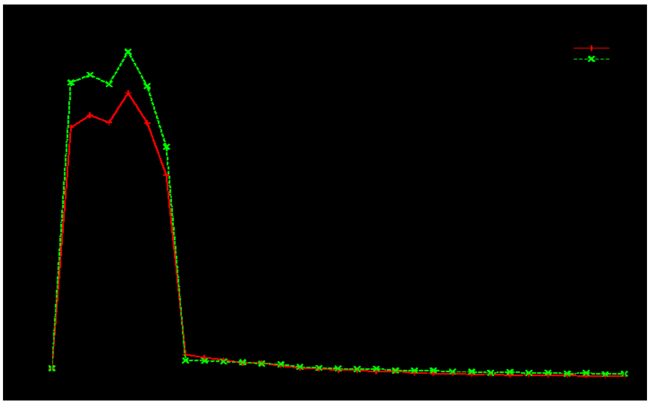


Figure 10 Simulation Result of 50 nodes in 100x100 meters

1.3 Research Gaps

Wireless Sensor Networks (WSN) have received considerable research attention with the major emphasis on optimizing the energy efficiency of the WSN, as the nodes are generally power-constrained due to limited battery power. However, considering the growing interest in real-time and event-driven applications, including environmental monitoring, healthcare services, and industrial control applications, the aspect of latency has also become a major concern for WSN, as the nodes should be capable of rapid data transmission. However, the majority of the existing solutions are unable to meet the requirements of low latency and high energy efficiency at the same time, as the solutions are generally focused on optimizing the energy efficiency of the WSN, which results in high latency, or vice versa.

The research proposal intends to create a low-latency, energy-efficient framework for efficient data transmission in WSNs by incorporating data aggregation, efficient routing, and smart scheduling. The research proposal focuses on the use of event-based data aggregation for reducing redundancy, efficient aggregation trees for reducing hops, as well as the adoption of non-myopic scheduling for efficient data transmission by considering the future state of the network. The overall approach of the proposed work can be explained as follows:

- Tree Generation: An optimized routing structure should be generated for efficient communication.
- Aggregation Mechanism: Event-based and data aggregation techniques should be applied for efficient data transmission.
- Scheduling Strategy: Adaptive 'Non-Myopic Scheduling' should be employed to achieve minimum delay and energy consumption.

Using this framework, the proposed work is focused on achieving low-delay and low-energy data transmission, ultimately contributing to the development of a complete framework for implementing the Rapid Data Transmission Technique for Wireless Sensor Networks.

1.4 Faults in WSN and Fault Tolerance Mechanisms

1. Node Fault: Antenna failures, circuit failures, and battery leaks might result from a range of extreme climatic circumstances, which will impair WSN performance.

2. Network Fault: Individual communication failures are more likely due to the large density of deployed nodes.

3. Sink Fault: The power supply and network infrastructure are usually the primary sources of sink failures, which result in the entire sensor network malfunctioning.

Fault Tolerance

1. Retransmission: The protocol chooses the way with the fewest hops and/or the least amount of energy usage among the several paths that are available. At last, the packet is acknowledged to the source by the sink node.

2. Replication: This prevents network failure brought on by local path failures by delivering copies of

the original packet across other paths.

3. LQI: Packet Reception Rate (PPR)-based Link Quality Indicator (Self Diagnosis)

4. Receive Signal Strength Indicator (RSSI). The signal power is expressed by the RSSI value, which is expressed in dBm. Usually, the values fall between -45 and -100 dBm. (Diagnosing Oneself)

5. Fuzzy Rule-Based System: LQI + RSSI + Hop Count + Weight

6. Agent-Based System: Cluster Node Agents, which measures LQI & RSSI. (Helpful in Faulty Cluster/Group Detection)

2 Problem Definition

Wireless Sensor Networks (WSN), as a promising technology for data collection in distributed systems, has attracted the attention of many researchers, but the existing data transmission approaches mainly consider the energy efficiency of the network while ignoring the latency requirements, which are essential for real-time and event-based applications. The conventional convergecast and data aggregation approaches reduce the number of redundant data transmissions but, at the same time, introduce additional latency due to buffering, multi-hop transmission, and scheduling inefficiency. Furthermore, the lack of a holistic framework for the optimization of tree formation, data aggregation, and scheduling results in increased probability of collision, variation of latency, and suboptimal usage of the resources of the network, especially for large-scale WSNs. Thus, the major problem identified in this research is to develop a novel data transmission scheme for WSNs that minimizes the latency as well as the energy consumption of the network, while ensuring the efficient communication of the data by optimizing the tree formation, data aggregation, and scheduling approaches for the WSN.

3 Objectives and scope of work

The primary aim and objective of this research is to develop a "Rapid Data Transmission Technique for Wireless Sensor Networks (WSNs)" that considers both low latency and high energy efficiency, thereby improving upon the limitations of previous techniques that only considered one aspect at a time. The proposed technique will help develop an integrated framework for WSNs that considers optimized tree generation, efficient data/event aggregation, and scheduling policies to enable rapid data transmission. Special emphasis will be given to reducing transmission delay, avoiding packet collisions, and improving network lifetime. The proposed system will also consider non-myopic scheduling and intelligent event aggregation techniques for better results in small and large networks.
The scope of the research will be to include simulation-based analysis and a preliminary real-time

implementation. The techniques that are being proposed will be validated using simulators for WSNs to check their performance in terms of latency, energy consumption, and scalability. At the same time, a preliminary implementation will be done using a sensor-based application like gas leak detection or indoor air pollution monitoring. It will start from single-node communication and will be extended to multiple nodes. In addition to that, the research will also include aspects of fault tolerance and reliability while making the techniques more feasible and implementable.

4 Original Contribution by the Thesis

The research work described in this thesis is primarily focused on proposing a new "Rapid Data Transmission Technique for Wireless Sensor Networks (WSNs)" that addresses one of the most important challenges related to WSNs, i.e., achieving low latency and energy efficiency at the same time. In addition to this, this proposed work also considers various aspects related to implementing this technique in real-time, making this work more feasible and applicable for practical scenarios.

The following are the three important contributions made in this research work:

1. Introduced a dual-objective framework for WSNs that integrates low latency and energy efficiency at the same time, which is a critical limitation in most existing techniques.
2. Proposed a unified algorithmic framework for WSNs that integrates tree generation, event-driven data aggregation, and non-myopic scheduling for improved network performance.
3. Validated the proposed technique through simulation and initial real-time implementation for improved network performance and applicability in various scenarios, including gas leak and indoor air pollution monitoring systems.

This research work proposes a new technique for achieving efficient and rapid data transmission for Wireless Sensor Networks.

5 Methodology, Results and Discussion

For this research, a hybrid method is proposed that incorporates physical implementation and simulation-based validation to create a Rapid Data Transmission Technique for Wireless Sensor Networks (WSNs). The proposed method is developed in a progressive manner that starts from proof-of-concept implementation and then progresses to algorithm development and evaluation through simulation.

5.1 Proposed Methodology

The proposed methodology integrates tree-based routing, aggregation, and scheduling to achieve efficient data transmission.

5.1.1 Network Topology Configurations

To analyze the impact of base station placement on network performance, multiple topology configurations are considered.

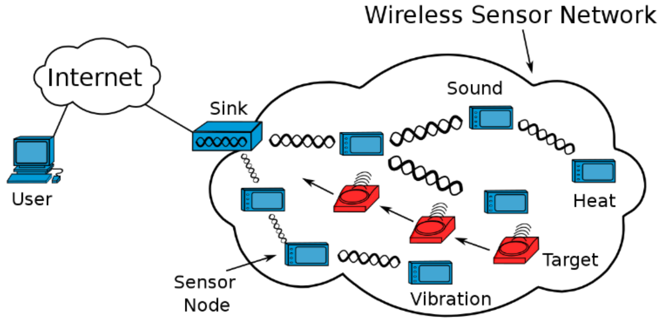


Figure 19 Base Station Placement in Corner Topology [19]

This figure illustrates a corner-based base station deployment, where the sink is placed at the boundary of the network. This configuration increases transmission distance and may lead to higher latency and energy consumption.

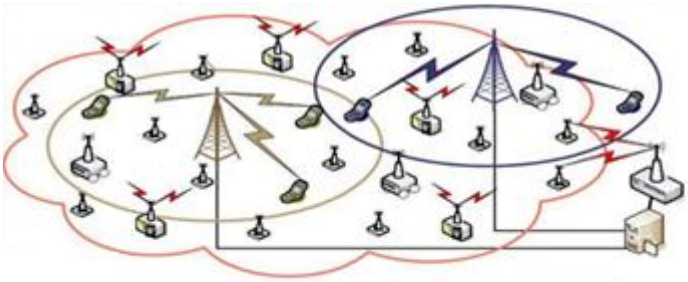


Figure 20 Base Station Placement in Centralized Topology [19]

This figure shows a centralized topology, where the sink is placed at the center. This configuration minimizes average hop count and improves both latency and energy efficiency.

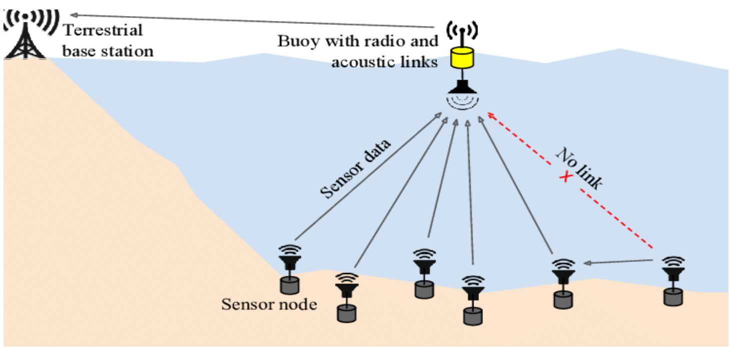


Figure 21 Underwater Sensor Network Topology [19]

This figure represents an underwater sensor network topology, highlighting challenges such as high delay, signal attenuation, and limited bandwidth.

5.1.2 Collision Avoidance and Efficient Communication Mechanisms

For efficient communication in WSNs, it is important to avoid collisions and redundant messages.

- RTS/Cts Mechanism: The Request to Send and Clear to Send signals are used to avoid collisions in WSNs.
- MACA Protocol: A slotted MAC protocol that avoids collisions by controlling access to the communication channel.
- CDMA and TDMA:
    - CDMA assigns unique codes to dominatees
    - TDMA assigns time slots to dominatees for efficient communication

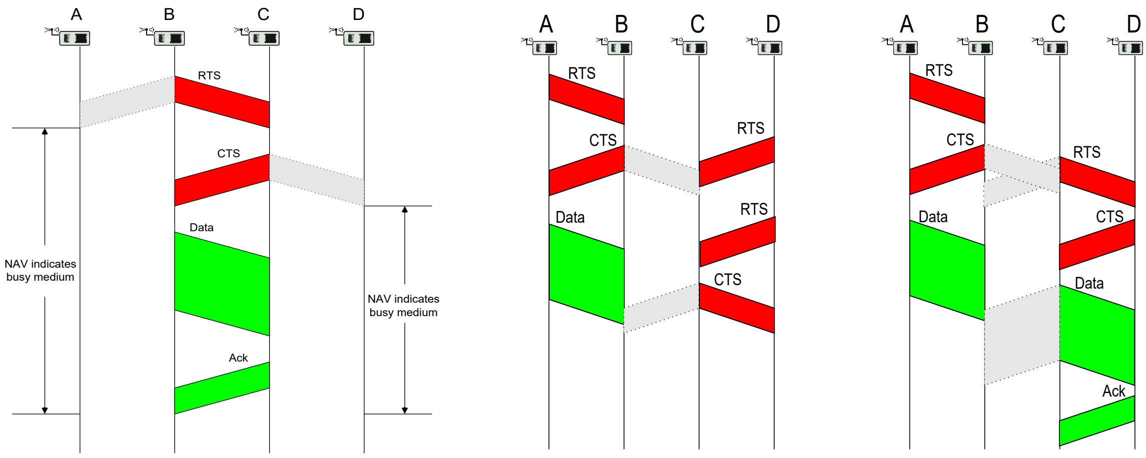


Figure 22 MACA-Based Collision Avoidance Mechanism

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

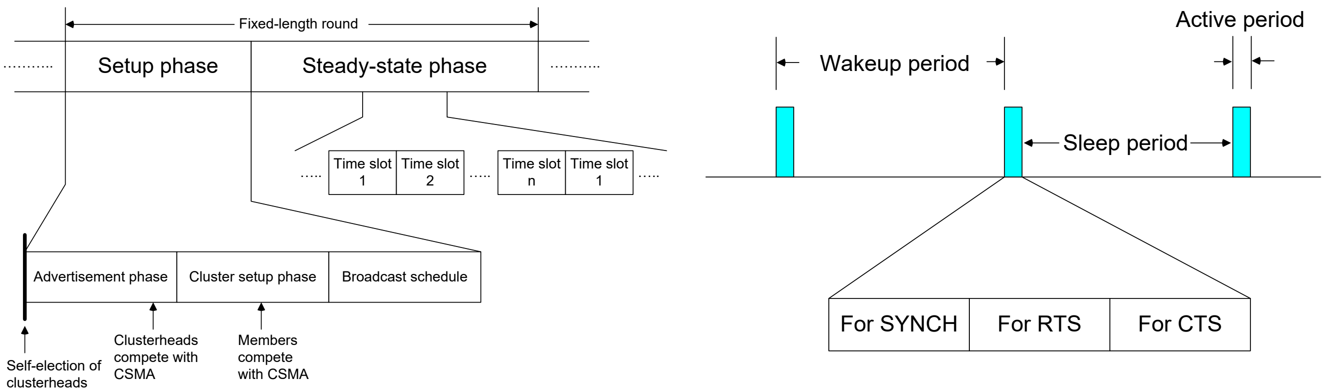


Figure 23 Sleep–Wake Mechanism for Energy Efficiency

5.2 Proposed Algorithm

The proposed algorithm is based on the greedy and hierarchical aggregation approach. In this approach, the dominatee node sends data to the nearest dominator.

Algorithm Phases

1. Each dominatee sends information to the nearby dominator with the lowest level (Greedy Approach).
2. Data is aggregated from lower-level dominators to higher-level dominators, and ultimately to the root of the aggregation tree, which serves as the network's topology center.
3. The topology center then uses the shortest path to send the combined data to the initial sink.

Phase 1: Data Aggregation to Dominators (Advertising Phase)

For each iteration

1: i=1 to Δ, perform the following steps:

2: Every dominator selects one adjacent dominatee node, whose data has not yet been collected, to act as a transmitter. These selected communication links together form a set denoted as L.

3: In case any interference or conflicts occur among the selected links in L, they are resolved using the procedure defined in Phase 2 of the algorithm.

4: After resolving conflicts, all non-interfering links in the set L are allowed to transmit data simultaneously.

5: Proceed to the next iteration by incrementing i.

Phase 2: Reconnection of Dominatees

1: Repeat while there exists at least one pair of interfering links

2: Select any such conflicting link pair $uizi$ and $ujzj$

3: Determine the corresponding sets Di and Dj according to the previously defined rules

Phase 3: Centralized Backbone Construction (EAS)

1: Build an event aggregation tree T' using the CDS approach. Eliminate unnecessary connector nodes so that each dominator connects to lower-level dominators using no more than 12 connectors within 2-hop distance. A connector node x (dominatee of dominator u) is considered redundant if its removal does not break connectivity between u and any of its 2-hop dominators. The resulting structure is the final aggregation tree T.

2: For each level i=R−1 down to 0:

3: Identify all dominator nodes at level i, denoted by Bi

4: For each dominator u∈Bi:

5: Determine the set $D2(u)$ of unmarked dominators located within two hops of u in the BFS tree and belonging to levels i+1or i+2.

6: Mark all nodes in $D2(u)$.

7: Each node $w \in D2(u)$ transmits aggregated data $f(Aw, X1, X2, \ldots, Xd)$ to its parent (connector node) in tree T, where Aw is its own data and $X1, \ldots, Xd$ are inputs received from its child nodes.

8: Each connector node z, acting as a parent of nodes in $D2(u)$, forwards aggregated data $f(X1, X2, \ldots, Xp)$ to dominator u, where $X1, \ldots, Xp$ are values collected from its children.

9: Decrement i and repeat the process for the next level.

10: Finally, the root node $v0$ transmits the aggregated result to the sink node using a shortest path algorithm.

Phase 4: Distributed Scheduling (TDMA-Based)

Input: Network $G$and aggregation tree T

Output: Time slot $TST[i]$for each node v_i

1: Each node $v_i$initializes its number of children $NoC[i]$and leaf status $Leaf[i]$according to tree T.

2: Construct the conflict set $CS[i]$based on tree $T$and interference relationships.

3: Compute $RdyCS[i] = CS[i] \cap \{j \mid j \text{ is a leaf node in } T\}$.

4: Set $TST[i] = 0$and $DONE = FALSE$.

5: Node $i$randomly generates a priority value r_i. Ordering is defined such that $(r_i, i) < (r_j, j)$if $r_i < r_j$, or if equal, $i < j$.

6: While $DONE = FALSE$:

7: If $NoC[i] = 0$, node $i$broadcasts a READY(i, r_i) message to all nodes in $CS[i]$.

8: If node $i$has the highest priority among all nodes in $RdyCS[i]$, it sends a FINISH(i) message to nodes in $CS[i]$and sets $DONE = TRUE$.

9: Upon receiving FINISH(j), node $i$removes $j$from $RdyCS[i]$and updates its time slot as

$$TST[i] = \max(TST[i], TST[j] + 1)$$

10: If node $j$is a child of node i, decrement $NoC[i]$by 1.

11: When node $i$receives READY(j, r_j), if $j \in CS[i]$, add $j$to $RdyCS[i]$.

12: Node $i$transmits its data during the assigned time slot $TST[i]$.

13: Finally, the root (topological center) forwards the aggregated result to the sink node.

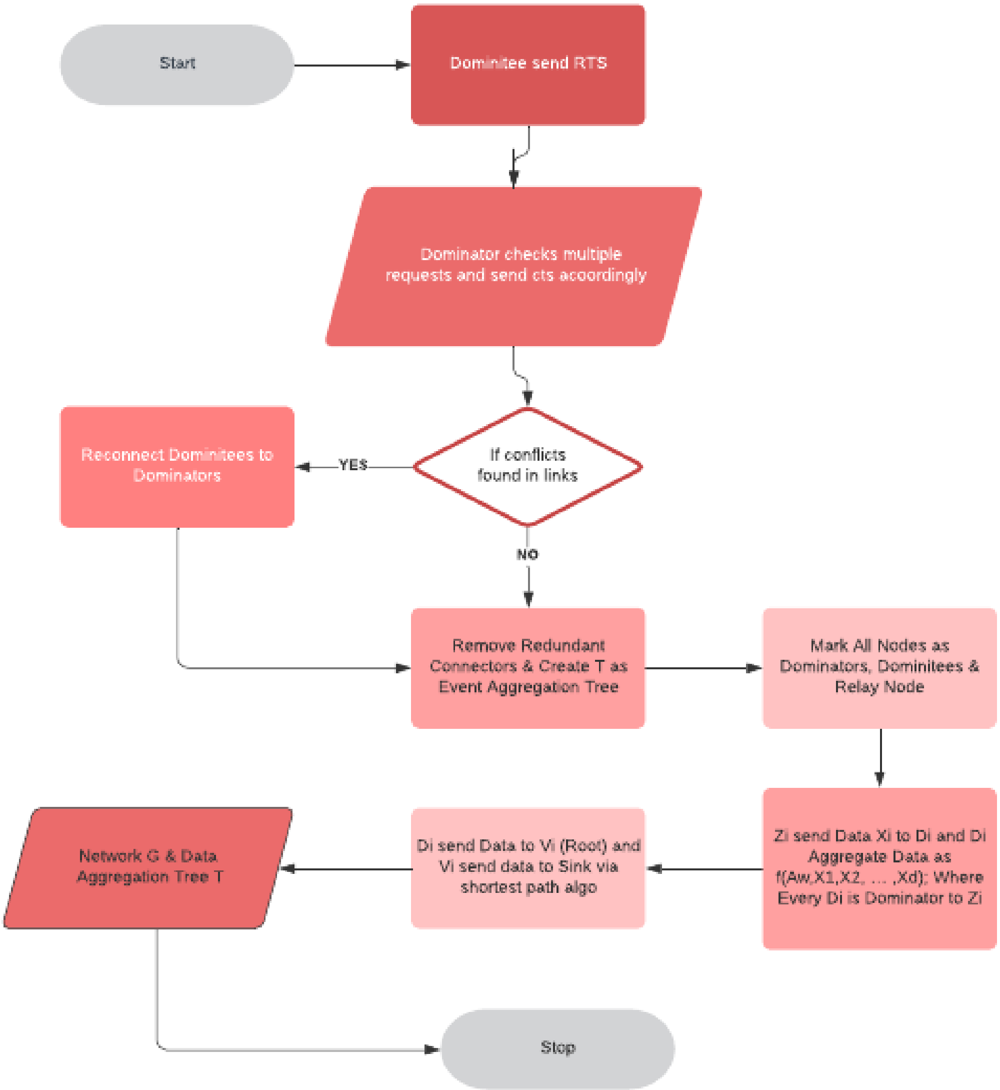


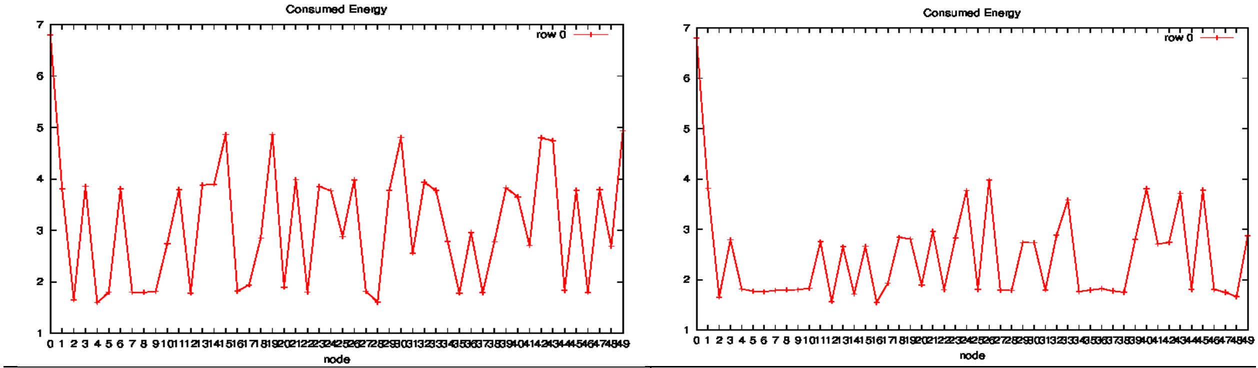
Figure 24 Flow chart for aggregation Tree Generation

5.3 Results and Discussion

The performance of the proposed Rapid Data Transmission Technique for WSNs is analyzed through extensive simulations using Castalia and NS2 simulators. The performance metrics considered in the evaluation are energy consumption, latency, and scalability of the proposed technique in comparison with other existing techniques.

5.3.1 Energy Consumption Analysis

Energy efficiency is one of the primary objectives of this research. The proposed aggregation-based approach is evaluated against a non-aggregation model.

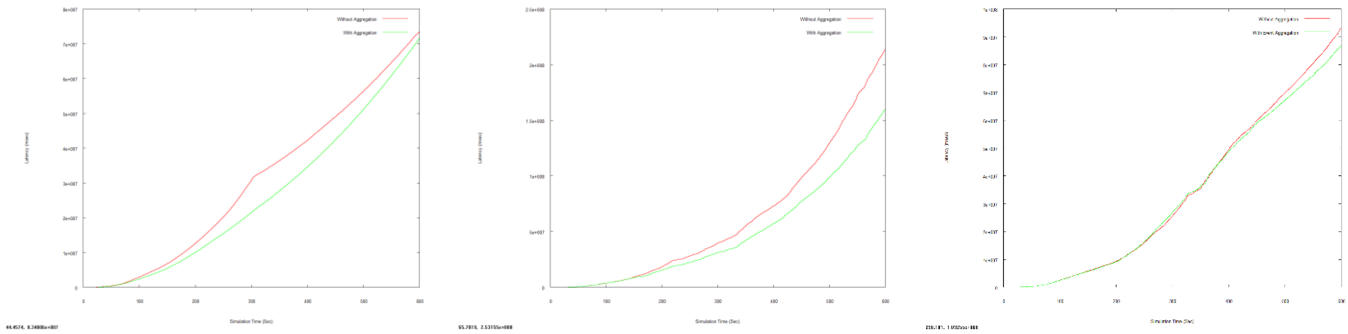


Without aggregation | With aggregation

Figure 25 Energy Simulation with and without Aggregation

5.3.2 Data Aggregation Performance

The scalability of the proposed data aggregation approach is evaluated across different network sizes.

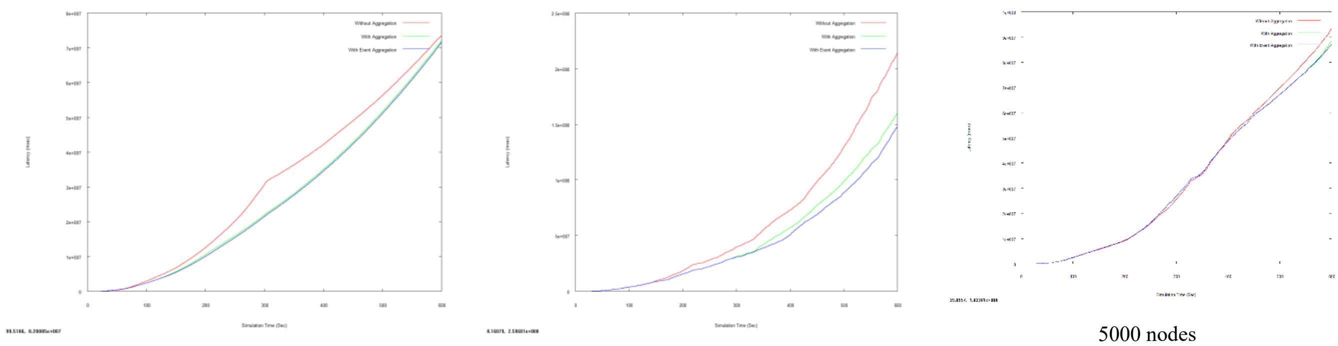


150 nodes | 1500 nodes | 5000 nodes

Figure 26 Data Aggregation Performance for 150, 1500, and 5000 Nodes

5.3.3 Event Aggregation Performance

Event aggregation is evaluated to analyze its impact on latency.



150 nodes | 1500 nodes | 5000 nodes

Figure 27 Event Aggregation Performance for 150, 1500, and 5000 Nodes

5.3.4 Latency Analysis

Latency is analyzed at multiple levels, including end-to-end delay, hop delay, and queueing delay.

- **End-to-End Latency:** Average: 150 ms, Maximum: 300 ms, Minimum: 50 ms

- **Hop Latency:** Average: 20 ms, Maximum: 50 ms, Minimum: 10 ms
- **Queueing Latency:** Average: 10 ms, Maximum: 30 ms, Minimum: 0 ms
- **Latency Distribution:** 50% of packets < 100 ms, 75% of packets < 150 ms, 90% of packets < 200 ms

These results confirm that the proposed method achieves low and stable latency, suitable for real-time applications.

5.3.5 Energy Efficiency Comparison

Detailed comparisons are conducted across different protocols and network sizes. This figure compares the average energy consumption per node across different protocols, showing that the proposed approach is more energy efficient.

- Energy Consumption Results: Total energy consumption: 234.5 Joules, Average energy consumption per node: 2.345 Joules, Minimum energy consumption: 0.321 Joules, Maximum energy consumption: 8.912 Joules
  - Event Aggregation Energy Breakdown: Data transmission energy: 45.6%, Data processing energy: 31.4%, Clustering overhead energy: 23.0%

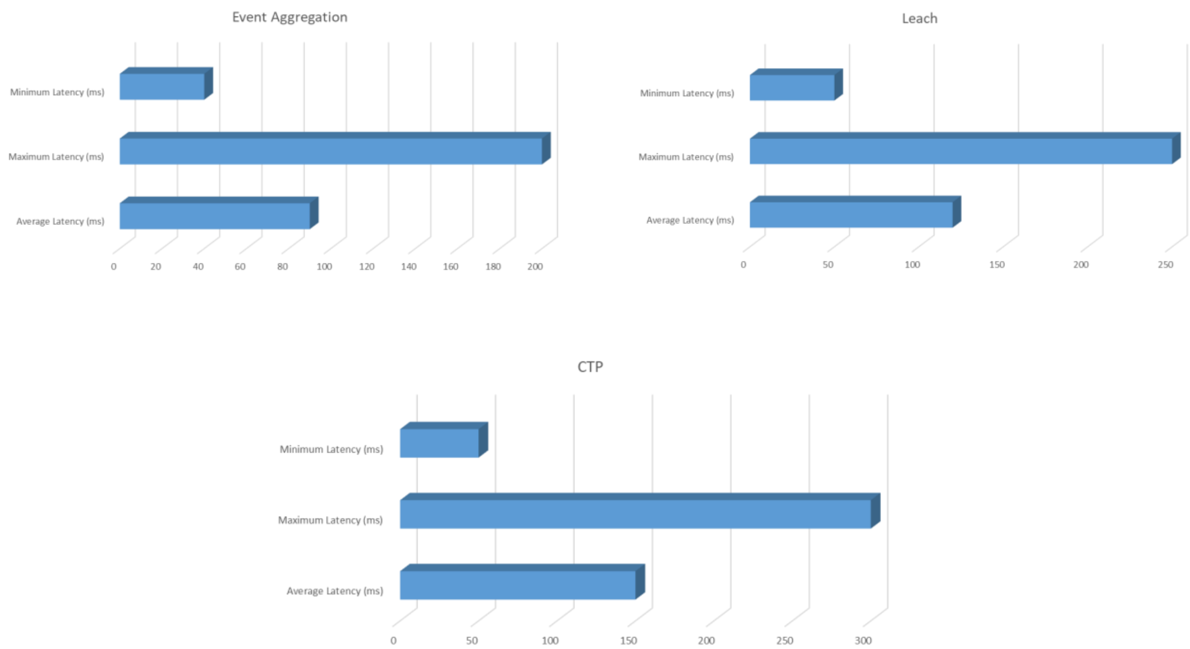
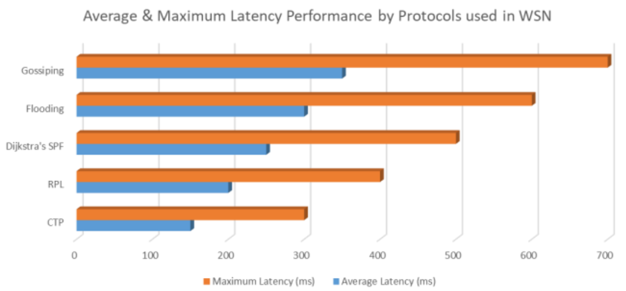


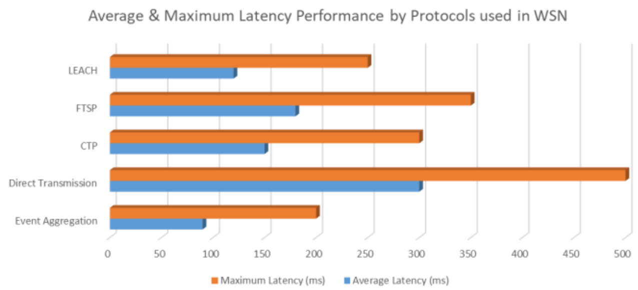
Figure 27 Latency Comparison

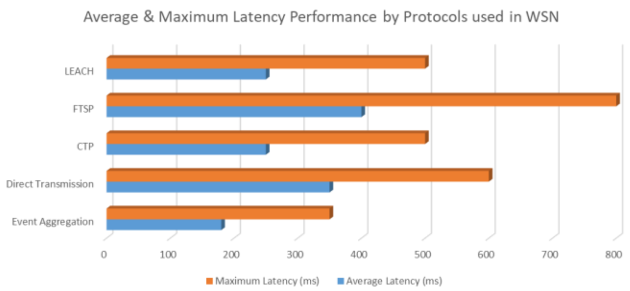
5.4 Average & Maximum Latency Performance by Protocols used in WSN

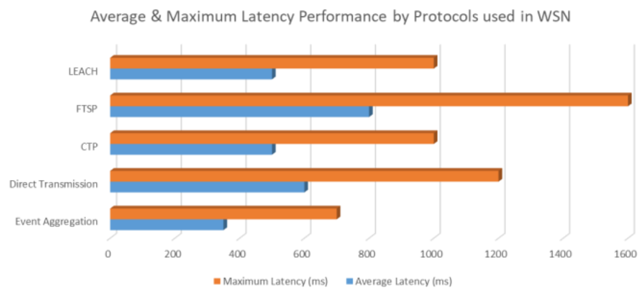
Table 1: Overall Comparison of Average Latency Performance by Protocols used in WSN

Network size	Protocol	Average Latency (ms)	Maximum Latency (ms)
100 Nodes	Event Aggregation	90	200
	Direct Transmission	300	500
	CTP	150	300
	FTSP	180	350
	LEACH	120	250
1000 Nodes	Event Aggregation	180	350
	Direct Transmission	350	600
	CTP	250	500
	FTSP	400	800
	LEACH	250	500
2000 Nodes	Event Aggregation	350	700
	Direct Transmission	600	1200
	CTP	500	1000
	FTSP	800	1600
	LEACH	500	1000
5000 Nodes	Event Aggregation	550	1100
	Direct Transmission	1200	2400
	CTP	900	1800
	FTSP	1600	3200
	LEACH	900	1800
1000 Nodes	Event Aggregation	1000	2000
	Direct Transmission	2500	5000
	CTP	1800	3600
	FTSP	3200	6400
	LEACH	1800	3600









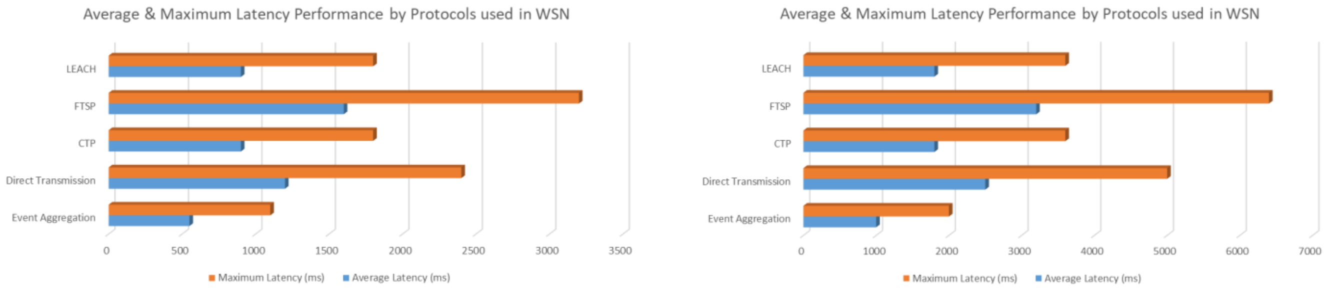


Figure 28 Average & Maximum Latency Performance by Protocols used in WSN with different Nodes

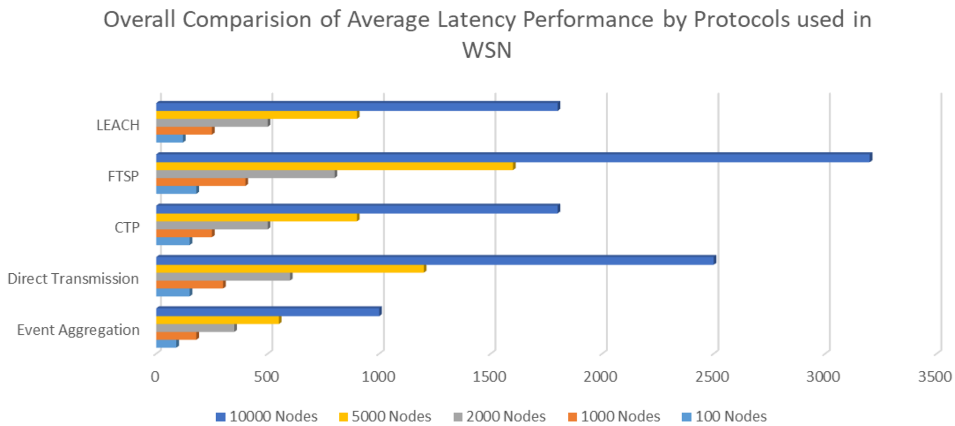


Figure 29 Overall Comparison of Average Latency Performance by Protocols used in WSN

6. List of Publications arising from Research Work

1. "Rapid Data Transmission through Tree Generation & Event Aggregation to Achieve Low Latency & Energy Saving in Wireless Sensor Networks.", International Journal of Advances in Signal and Image Sciences (IJASIS) 2025, (ISSN 2457-0370, Vol. 11 No. 2, Page 127-141)
2. “Scheduling with Multiple Channels for Rapid Convergecast in Wireless Sensor Networks”: JETIR Volume 7 Issue 12 DEC 2020
3. Energy Efficient and Fast Data Transmission Techniques for Wireless Sensor Networks, GIT JET Special Edition ICDSIA-2020 Twelfth Volume-I, 2020, (ISSN 2249 – 615 Page 17-20) (Conference Preceding Publication).

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