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Energy-Based Cluster Head Selection in WSN

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Wireless Sensor Networks (WSN) are the collection of sensor nodes, deployed in an ad hoc fashion and mostly powered by batteries. Therefore, efficient energy utilization has remained a vital parameter in designing and developing of WSNs to extend the network lifetime. In any network, routing protocols operate for selecting routes for the transfer of data packets from source to destination. Ad Hoc On-Demand Distance Vector (AODV) is a routing protocol used in various wireless ad hoc networks for transmitting data from source node to destination through intermediate motes. Hence, the efficient path selection mechanism can significantly improve energy utilization and elongate the lifetime of the network. This paper provides an investigation using the AODV routing protocol, based on the Cluster Head (CH) selection mechanism and shortest path selection between a source node, CH, and sink using multi-hop communication. The proposed scenarios significantly reduce energy consumption by selecting the shortest path between the source, cluster head, and sink. The Matlab simulation results show the comparison between AODV and Cluster head-based AODV (CH-AODV), indicating the CH-AODV consumes much less energy compared to normal AODV protocol.
Keywords: Energy Consumption; Clustering; Routing; AODV.

Introduction:

WSN comprises numerous autonomously distributed sensor nodes, also called motes, each having its processing, sensing, communication, memory, and power unit. These networks are predominantly deployed in challenging environments where natural phenomena and environmental changes occur. The WSN technology finds application in health sectors, industries, homes, and military battlefields for monitoring purposes. In WSN, each mote senses the event and forwards the data to the cluster head. The cluster head serves as a data aggregator, collecting information from multiple nodes and forwarding it to a sink node. The communication between these nodes can be single or multi-hop communication based on various parameters and network considerations such as network size, distance between sink, CH and sensing node, routing protocol, etc. Routing protocols play an important role in sending data between motes and base stations (BS) for communication. Protocol classification depends on network structure, node participation, mode of functioning, and type of targeted application. Various routing protocols are proposed by researchers to improve the communication and life span of sensor nodes in WSN. In many applications, motes are deployed in an ad hoc fashion where they must autonomously organize themselves in a wireless communication network. Each mote is powered using batteries and deployed in complex and dangerous areas in most application scenarios where they operate without any attendance for relatively longer periods. In such cases, it becomes inconvenient to change or recharge the batteries of depleted nodes. Therefore, energy efficiency is one of the major concerns in designing the protocol for WSN.

Novelty Statement:

In Ad-hoc On-Demand Distance Vector (AODV) routing, hop count is the primary criterion for selecting a path between source and destination nodes. In networks with a large number of nodes, there can be a higher number of intermediate nodes, which translates to a higher hop count. Energy consumption in AODV can be categorized as useful and wasteful parameters. Useful parameters include transmission, storage, processing, and forwarding. Conversely, wasteful parameters include idle listening, retransmission, overhearing, and over-emitting. These wasteful parameters significantly increase overall energy consumption, and end-to-end delay, and ultimately affect the network's lifetime. This paper proposes a novel efficient cluster head selection method that significantly reduces the number of hops required and eliminates the need for idle listening, retransmission, overhearing, and over-emitting from all nodes except the chosen cluster heads. In the clustering approach, the nodes are close to the cluster head compared to the sink. In the CH-AODV protocol, we considered a grid topology to find out the effects of the clustering approach. The clustering is achieved by dividing the network into four and six clusters. The position of the cluster head is changed based on the closeness to sink and hop count from nodes within the cluster. The hop count is reduced using this approach which has significantly reduced the overall energy consumption of the network.

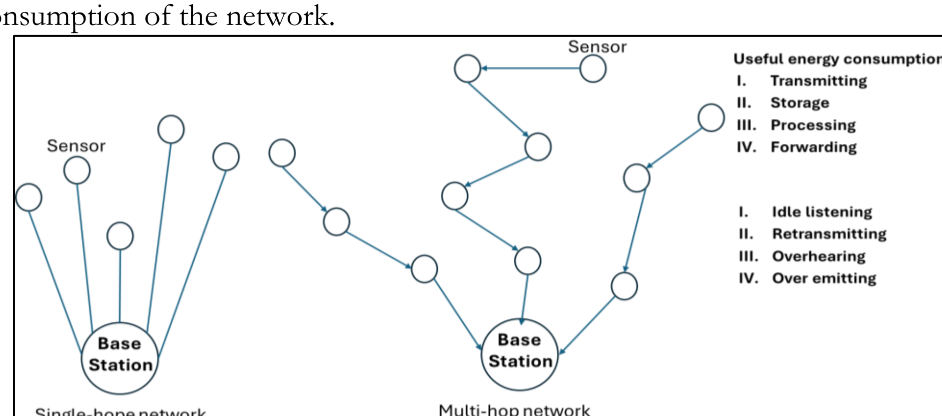

Figure 1: Single-hop vs multi-hop WSN network with useful and wasteful energy consumption sources.

Related Literature:

In WSN, energy is a scarce resource, therefore the significance of developing an energy-efficient mechanism cannot be exaggerated. In single-hop WSN networks the sensing nodes are directly connected to the base station or sink of the systems while in multi-hop networks they are indirectly connected through intermediate nodes as shown in Figure 1. It is shown in the literature that multi-hop networks are the most energy-efficient systems. The problem of energy consumption is addressed by many researchers in their work. Some energy-efficient techniques may be based on application requirements and network building whereas the conclusive objective is to minimize the energy consumption during network processes. To reduce the energy consumption by sensor nodes, placed at a large distance from BSs, an energy-balanced approach protocol [1] is proposed in which cluster head selection is based on the highest energy level of sensor nodes while in re-clustered CH selection phase, the previously selected CHs are examined against defined threshold. The CHs are retained which have higher energy levels than the defined threshold for the next round. This saves energy, which is dissipated in the CHs selection phase. In [2], Dijkstra's algorithm for the shortest path is combined with cluster head LEACH. The proposed method randomly selects the cluster heads like the standard LEACH protocol. Later, it checks for the load on CHs; if it is lower than the threshold, the node is retained as CH and added to the path to BS or the source node finds an optimal path based on the Dijkstra algorithm which is the best solution for the selection of lowest path cost. However, the algorithm is complex which increases the computational and processing delay, significantly affecting the energy consumption. In [3], the author proposed the mathematical model where BSs are placed at appropriate locations to minimize the Euclidean distances from the source node to BS. The cluster is formed using Euclidian distance and Hessian matrix is used to identify the location of BSs which results in a reduction of energy consumption through short-range communication links between source and destination. The energy harvesting-based clustering (EH-Clustering) approach is proposed in [4], the paper addresses the problem of cluster failure when the energy of the cluster head is depleted. The author proposed an additional energy source i.e., an Energy harvesting system. It provides continuous energy to CH, which is harvested from external sources, stored, and converted into useful power through a power management unit.

Above discussed method describes the single hop communication where the problem is associated with the distance between the sensor nodes and BSs which causes CHs to dissipate a lot of energy in the transfer of data from sensor nodes to BS. Therefore, recent research work is mostly focused on multi-hop communication because the messages are transferred using intermediate motes between source and destination which significantly reduces the energy consumption dissipated in transmission compared to single-hop communication. In [5], the AODV protocol is proposed using cellular automata mechanism (AODV-ECA). The protocol builds the neighbor table for each node and records their residual energy through hello messages. It also introduces the irregular cellular automata mechanism to make topology flexible. The AODV-ECA offers better energy efficiency and performance. However, it increases the overhead of the network because of additional residual energy information in hello messages. In [6], single-hop and multi-hop clustering approaches are compared for WSN. Simulation results exhibit that the multi-hop clustering approach gives more energy-efficient results. In [7], the shortest path balancing, and energy load balancing algorithm are simulated using NS2 for grid topology using a multi-hop approach. The results show that the proposed scheme saves over 8 % energy per node and improves the throughput by 18.2 % with data aggregation techniques through multi-hop communication. Energy consumption and network lifetime are major concerns in heterogenous WSNs. A novel hybrid fuzzy ABC-based algorithm in multi-hop WSN is proposed in [8], to increase the lifespan of the network and balance the energy consumption equilibrium in heterogeneous networks. The selection of CH depends upon the power availability, signal strength, and distance between nodes. The experimental results manifest that the proposed method improves the lifespan of the network as well as reduces the end-to-end delay and packet loss rate compared to other selection methods tested in simulation. However, a paramount challenge with multi-hop communication techniques is a tradeoff between finding distance efficient path (minimum hop count) and energy efficient path (path on which nodes have maximum residual energy) to the BS. An Energy Prediction based selection method based on LEACH (LEACH-EP) is proposed in [9]. In [10] a new clustering algorithm is proposed for WSNs to reduce energy consumption and thus prolong the life of the WSNs. The Cluster Centered Cluster Head Selection Algorithm (C3HA), which is developed in line with this objective, gives a new perspective to the selection of CH while creating a more efficient WSN than the popular clustering algorithms LEACH, and PEGASIS. In [11], an energy-efficient cluster head selection using an improved version of the gray wolf optimization (EECHIGWO) algorithm to enhance the energy efficiency and lifetime of WSN. In [12], an optimal cluster head selection (CHS) model is developed regarding secure and energy-aware routing in the Wireless Sensor Network (WSN). Existing energy-based cluster head selection methods in practical Wireless Sensor Network (WSN) deployments face several challenges and limitations, like:

Energy Efficiency vs. Network Lifetime:

- **Challenge:** Balancing energy efficiency while extending network lifetime is complex.
- **Limitation:** Some methods may focus too much on immediate energy savings, leading to premature node failures and reduced overall network lifespan [13].

Random vs. Optimal CH Selection:

- **Challenge:** Random CH selection causes poor connectivity and unexpected node failures.
- **Limitation:** Optimal CH selection enhances performance but requires more computational overhead and communication

Dynamic Network Conditions:

- **Challenge:** WSNs operate in dynamic environments (e.g., changing topologies, varying traffic).
- **Limitation:** Fixed CH selection methods struggle to adapt to real-time changes, affecting energy balance [13]

Scalability and Load Distribution:

- **Challenge:** As WSNs grow, scalability becomes critical.
- **Limitation:** Some methods don't distribute the load evenly among CHs, leading to energy disparities and early node depletion [13]

Fault Tolerance and Node Failures:

- **Challenge:** Ensuring fault tolerance while minimizing energy consumption.
- Limitatio**n:** CH failures impact network stability, especially in critical applications [13].

Heterogeneous Nodes:

- **Challenge:** WSNs often have nodes with varying energy levels and capabilities.
- **Limitation:** CH selection methods must account for heterogeneity to avoid energy imbalances [13].

Trade-offs in Clustering Algorithms:

- **Challenge:** Choosing the right clustering algorithm.
- **Limitation:** Each algorithm has trade-offs (e.g., LEACH, PEGASIS) in terms of energy efficiency, complexity, and scalability [10]

In summary, achieving an optimal balance between energy efficiency, network lifetime, and adaptability remains a challenge. Researchers continue to explore innovative solutions to address these limitations. In this paper, we apply the cluster head approach to AODV protocol and find the shortest path from source to CH to sink/BS for reducing energy consumption. The proposed scenarios are compared with standard AODV based on energy utilization. The rest of the paper is organized as follows, section II demonstrates the system model and parameters set for the simulation. Section III discusses the simulation results of comparison and different scenarios considered in this paper. Lastly, in section IV the paper is concluded.

Methodology:

System Model:

The model consists of 101 sensor nodes, set up in grid topology. Figure 2 exhibits the arrangement of sensor nodes in the grid formation.

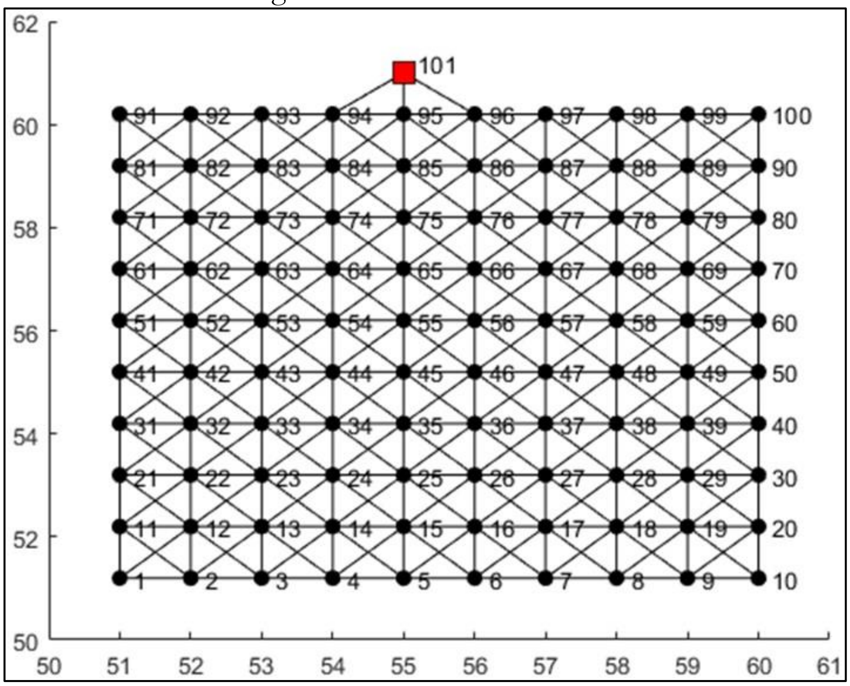

Figure 2: Arrangement of nodes in a grid topology.

The methodology adapted to simulate the proposed system and for the packet transmission is shown in Figures 3 and 4 respectively.

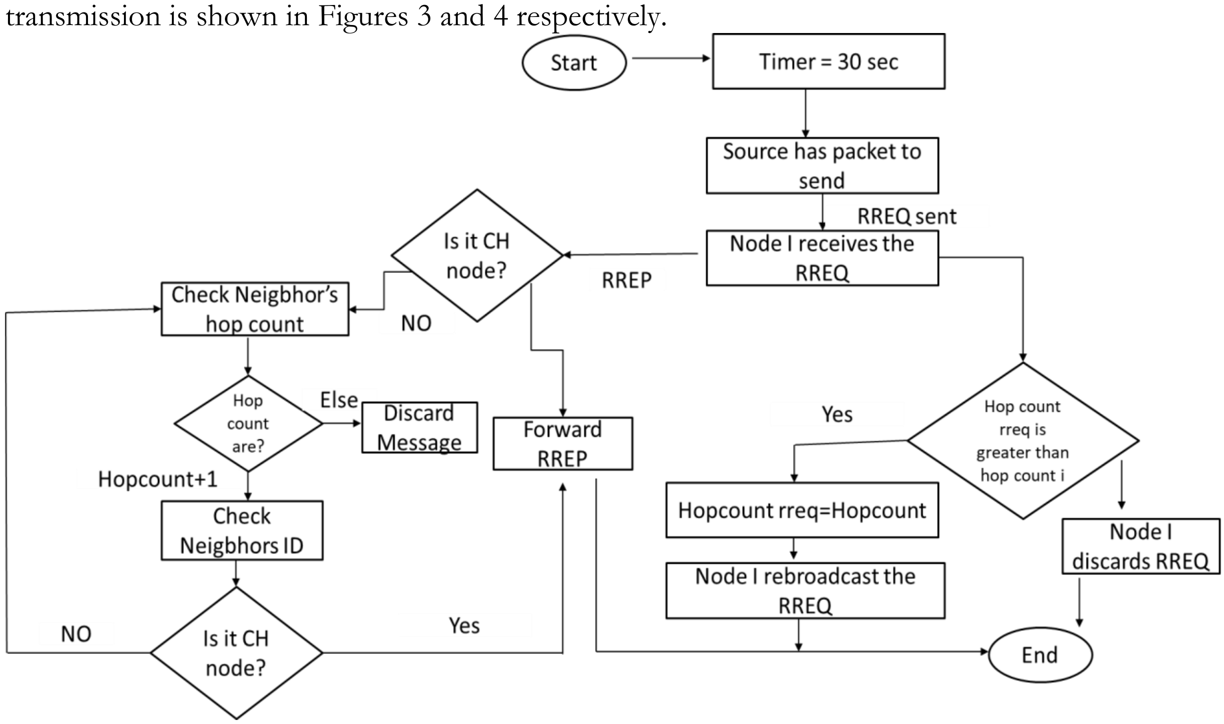

Figure 3: Methodology for the path establishment.

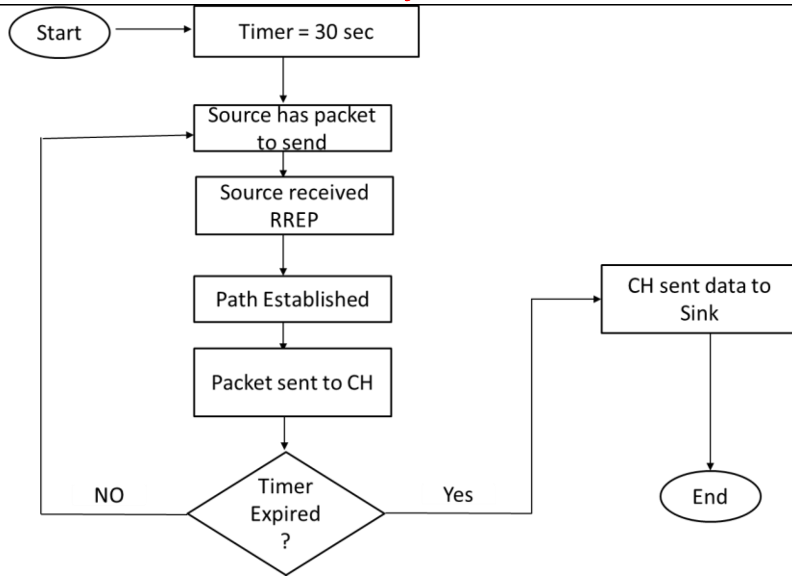

Figure 4: Methodology for packet transmission.

The investigation was carried out under five scenarios. In the first scenario, the standard AODV (Ad hoc On-Demand Distance Vector) protocol was implemented. In the remaining scenarios, a clustering approach was integrated with the AODV protocol. Messages were forwarded through intermediate nodes using multi-hop communication. The source node was randomly selected in each scenario, while the sink (Node 101) remained fixed. In the second and third scenarios, the network topology was divided into four clusters, each with a designated cluster head. In the fourth and fifth scenarios, the topology was divided into six clusters, each also having its cluster head. The selection of the cluster head was based on the centrality of the node within the cluster and the energy consumption of each setting.

Table 1: Simulation Parameters

S. No	Notation	Parameter	Value
1	-	Simulation time	30 sec
2	-	Routing	AODV
3	N	No. of Nodes	101
4	V	Voltage	3.3 volts
5	R	Sample rate (packet/sec)	1/600
6	Csleep	Sleep Current (mA)	60
7	Ctxb	1 byte transmit current (mA)	98
8	Crxb	1 byte receive current (mA)	71.2
9	Cidle	Idle current (mA)	15
10	Cdata	Sensor sample current (mA)	75
11	Ttxb	Time to transit 1 byte (sec)	0.3
12	Trxb	Time to receive 1 byte (sec)	0.3
13	Tdata	Sensor sample time (sec)	1.2
14	Tidle	Idle state time (sec)	10
15	K	No. of bytes	1600

In the WSN, the energy consumed by the node consists of receiving, transmitting, sampling data, sleeping, and listening to radio channels for messages. Equation 1 is used to determine the overall energy consumption by each node during operation.

$$E = E_r + E_{tx} + E_d + E_{sleep} + E_{listen} \qquad (1)$$

The energy consumed during the driving of the radio subsystem by the sensor node in transmitting, Equation, (2) and (3) shows the transmission time and energy consumed by each node.

$$t_{tx} = r * k * t_{txb} \quad (2)$$

$$E_{tx} = t_{tx} * c_{txb} * V \quad (3)$$

Where t_{txb} is the time required to transmit one byte of data, r is the duty cycle, k is the total number of bytes, c_{txb} is the total time required to transmit k bytes of data, is current consumption and V is the voltage required.

Similarly, the energy consumed during receiving, E_{rx}, can be calculated using (4) and (5).

$$t_{rx} = r * n * k * t_{rxb} \quad (4)$$

$$E_{rx} = t_{rx} * c_{rxb} * V \quad (5)$$

Where t_{rxb} is the time required to receive one byte of data, n is the total number of nodes participating intermediate nodes, t_{rx} is the total time required to receive k bytes of data, c_{rxb} is the current consumption for reception of data. Sensors are the fundamental part of WSN and must be considered in calculating the energy consumption by the node. Equation 6 shows the parameters required for sensing the event.

$$E_d = t_{data} * r * c_{data} * V \quad (6)$$

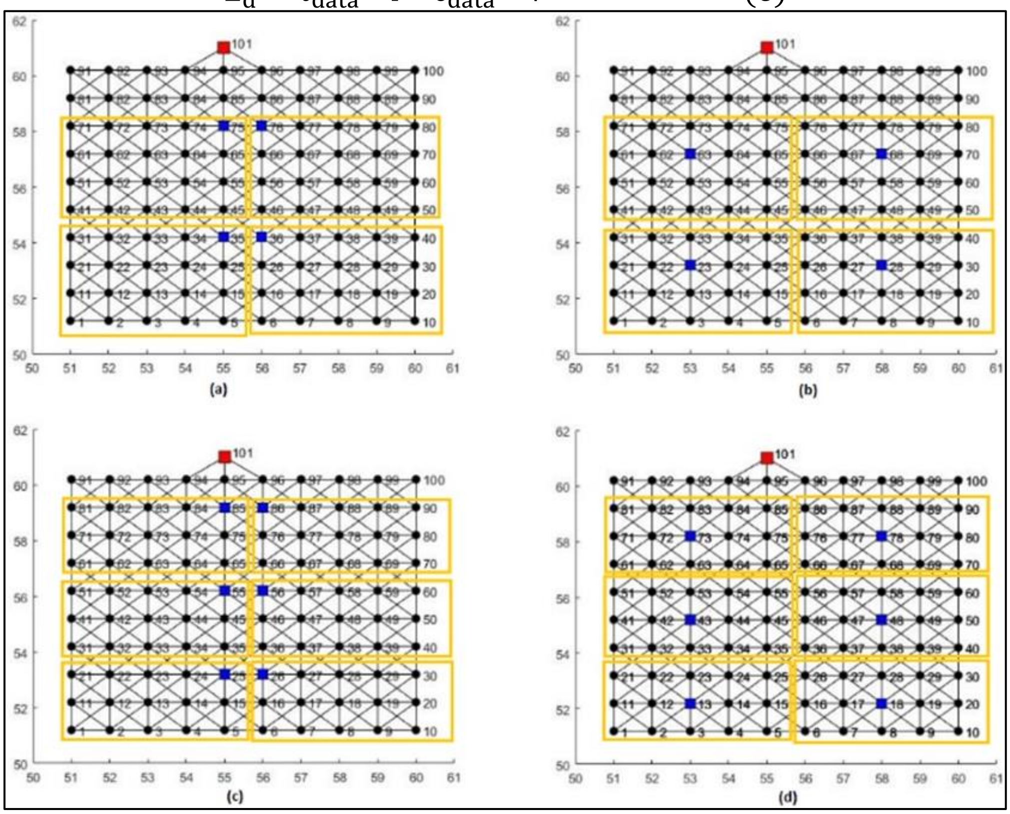

Figure 5: Formation of clusters and selected CHs.

Where t_{data} is the time required and c_{data} is currently consumed by the sensor in detecting the event. Considering the topology, each scenario has been simulated for 30 seconds. The parameters used for the estimation of energy consumption are given in Table 1. The optimal number of nodes depends on the network size, coverage area, and application requirements. In some protocols like LEACH, nodes randomly choose to become cluster heads based on a predefined threshold. Intelligent optimization algorithms (e.g., gray wolf optimization, genetic algorithms) can help select optimal cluster heads [14]. More cluster heads improve energy efficiency but increase overhead. Fewer cluster heads may lead to uneven load distribution. Therefore, in this work, 101 nodes are taken to avoid uneven load distribution and reduced efficiency. Similarly, Longer simulation times allow for observing network behavior over extended periods. We must ensure sufficient time for transient effects (e.g., initial setup, convergence). Balance simulation time with computational resources and research objectives. Therefore, a manageable simulation time of 30 seconds is chosen in this work. Furthermore, the computation of energy was investigated by changing the number of CHs and their location in each scenario. Figure 5 manifests the clusters and their member nodes while selected CHs are listed in Table 2.

Table 2: Scenarios and their respective CHs

Scenario	No. of Clusters	CHs ID	Figure
S1	0	0	Figure 2
S2	4	35, 36, 75, 76	Figure 5(a)
S3	4	23, 28, 63, 68	Figure 5(b)
S4	6	25, 26, 55, 56, 85, 86	Figure 5(c)
S5	6	13, 18, 43, 48, 73, 78	Figure 5(d)

Simulation Parameters Overview:

The simulation duration of 30 seconds enables a comprehensive observation of network behavior, balancing computational efficiency and thorough analysis while avoiding the omission of transient effects. The AODV (Ad Hoc On-Demand Distance Vector) routing protocol was selected for its reactive nature, establishing routes only when necessary, thereby minimizing overhead in dynamic networks with fluctuating topologies. The network consists of 101 nodes, which is suitable for studying medium-sized Wireless Sensor Networks (WSNs). This setup provides valuable insights into scalability, energy consumption patterns, and communication efficiency. Sensor nodes operate at a voltage of 3.3 volts, impacting both energy consumption and transmission range, which are crucial for maintaining operational longevity. A sample rate of 1/600 packets per second determines the frequency at which nodes collect and transmit data. This rate optimizes energy use while ensuring that data accuracy meets operational requirements. The current parameters specified include Sleep Current (Csleep), Transmit Current (Ctxb), Receive Current (Crxb), Idle Current (Cidle), and Sensor Sample Current (Cdata), each of which influences energy profiles during various node states. Time parameters such as Time to Transmit 1 Byte (Ttxb), Time to Receive 1 Byte (Trxb), Sensor Sample Time (Tdata), and Idle State Time (Tidle) delineate operational durations critical for energy management and data handling efficiency. Additionally, the data size of 1600 bytes transmitted during the simulation directly impacts energy consumption and overall network performance, shaping a comprehensive evaluation of WSN capabilities under realistic conditions.

Simulation Results and Discussion:

Considering the random occurrence of changes in natural phenomena and environments, randomness has been incorporated into the simulation by selecting the source node arbitrarily while keeping the sink node fixed across all investigations. Due to this arbitrary source selection, the model was simulated multiple times, resulting in randomized outcomes in the obtained results.

Scenario 1 (S1):

In this scenario, the standard AODV protocol is implemented and simulated for 30 seconds. The observed energy consumption per node is shown in Figure 6. According to the topology, the simulation results indicate that the nodes in the first four tiers of the sink consume more energy because they act as gateways to the destination node. These four tiers, as per Scenario 1, include nodes that consumed more than 100 joules, which are detailed in Table 3.

Table 3: First four Tiers as per Scenario 1

S No	Tier	Nodes	Nodes consuming more than 100 joules
1	1st	84, 85, 86, 94, 95, 96	84, 85, 86, 94, 95, 96
2	2nd	73, 74, 75, 76, 77, 83, 87, 93, 97	74, 75, 76, 93
3	3rd	62, 63, 64, 65, 66, 67, 68, 72, 78, 82, 88, 92, 98	63, 65, 66, 67
4	4th	51, 52, 53, 54, 55, 56, 57, 58, 59, 61, 69, 71, 79, 81, 89, 91, 99	53, 56, 57

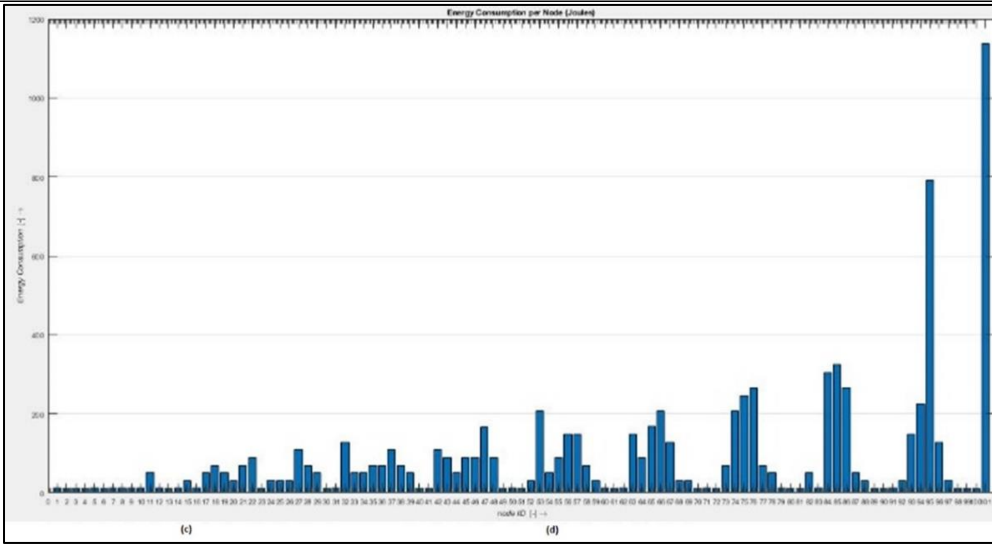

Figure 6: Energy Consumption per node as per scenario 1.

Most of the network load is concentrated in the first four tiers and the sink node, leading to faster battery depletion in these nodes. This rapid energy dissipation in some nodes can cause portions of the network to fail, resulting in communication disruptions with the sink. Figure 11 illustrates the total energy consumption per node.

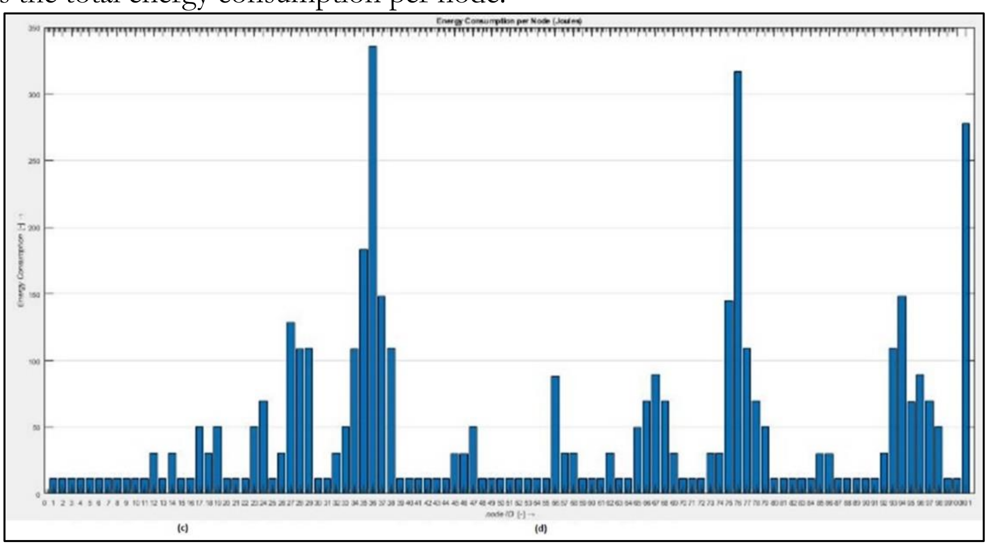

Figure 7: Energy Consumption per node as per scenario 2.

Scenario 2 (S2):

Figure 7 illustrates the energy consumption per node in Scenario 2. In this scenario, nodes 35, 36, 75, and 76 were selected as cluster heads (CHs) and are located at the edge of their respective clusters. Figure 5(a) depicts the cluster configuration. The source node was randomly selected and transmitted data to the assigned CH, with the process continuing for 30 seconds. Subsequently, CHs 35 and 36 forwarded the aggregated data to CHs 75 and 76, which then relayed the data to the sink using multi-hop communication. As shown in Figure 7, the network load is concentrated on the CHs, which reduces energy consumption at the sink. According to the topology and graph, nodes 27, 28, 29, 34, 37, 38, 77, 93, and 94 consumed more than 100 joules, excluding the CHs as they were involved in data aggregation. This approach significantly lowers overall energy consumption, balances network load, and alleviates energy depletion issues for nodes near the sink. The total energy consumption by nodes is presented in Figure 11, and the energy savings achieved with this approach is 42.114% compared to Scenario 1, as detailed in Table 4.

Table 4: Comparative results of total consumed and saved energy

Scenario	Total Energy Consumed (TE) (Joules)	Saved Energy (%)
S1	7345.762 J	0
S2	4250.428 J	42.114 %
S3	3466.877 J	52.785 %
S4	3745.241 J	48.994 %
S5	2796.756 J	62.279 %

Scenario 3 (S3):

In Scenario 3, cluster heads (CHs) were selected based on their centrality within their clusters, as depicted in the topology shown in Figure 5(b). The chosen CHs are nodes 23, 28, 63, and 68. Energy consumption per node is displayed in Figure 8. The source node is selected randomly and sends data to the respective CHs, which then communicate with CHs 63 and 68. These CHs further forward the aggregated data to the sink. The selection of CHs 63 and 68 for inter-CH communication is also random. The results indicate that only node 96 consumed more than 100 joules, excluding CHs and the sink. This scheme has further reduced energy consumption and balanced the network load. The improvement in energy utilization is attributed to the centralized CHs, which minimize the number of intermediate nodes between the source and CHs. This results in an overall energy savings of 52.785% and 18.435% compared to Scenarios 1 and 2, respectively, as detailed in Table 4, with comparative results shown in Figure 11.

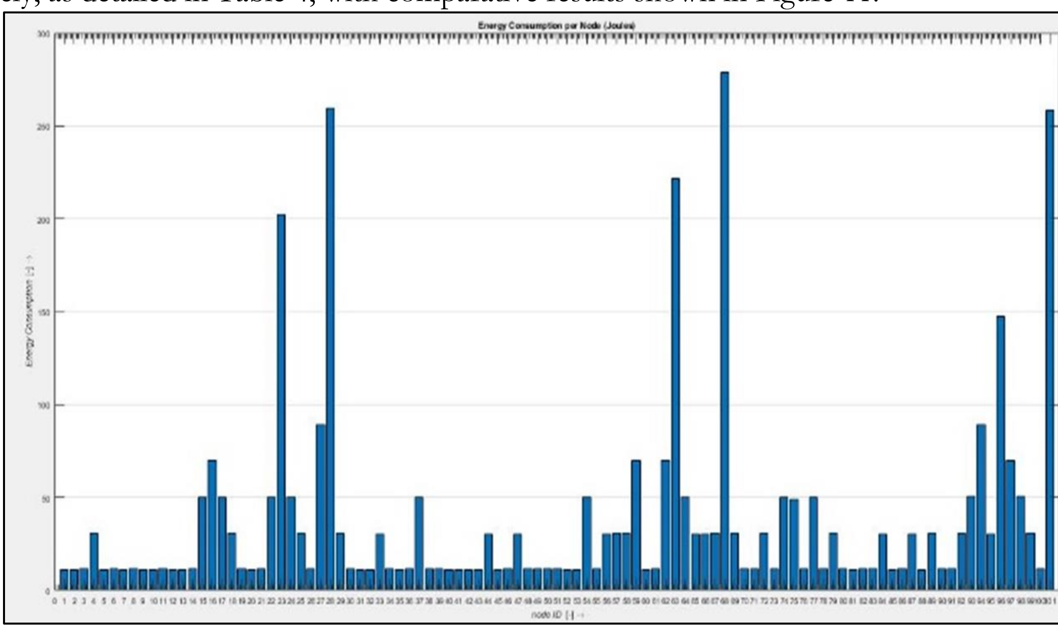

Figure 8: Energy Consumption per node as per scenario 3.

Scenario 4 (S4):

Figure 9 displays the energy consumption per node for the fourth scenario, while the cluster formation is illustrated in Figure 5(c). In this scenario, six clusters were established with nodes 25, 26, 55, 56, 85, and 86 selected as cluster heads (CHs) located at the edges. The source node selection follows the same approach as in Scenario 3. CHs 25 and 26 forward data to CHs 55 and 56, which then pass the data to CHs 85 and 86 through a random selection process. The results indicate that nodes 65, 66, 78, and 87 consumed more than 100 joules, excluding CHs. The overall energy consumption of the network was reduced compared to Scenarios 1 and 2. Figure 11 shows that the total energy consumption in this scenario is 11.885% less than in Scenario 2 and 7.434% higher than in Scenario 3. The total energy saved is 48.994%, as detailed in Table 4.

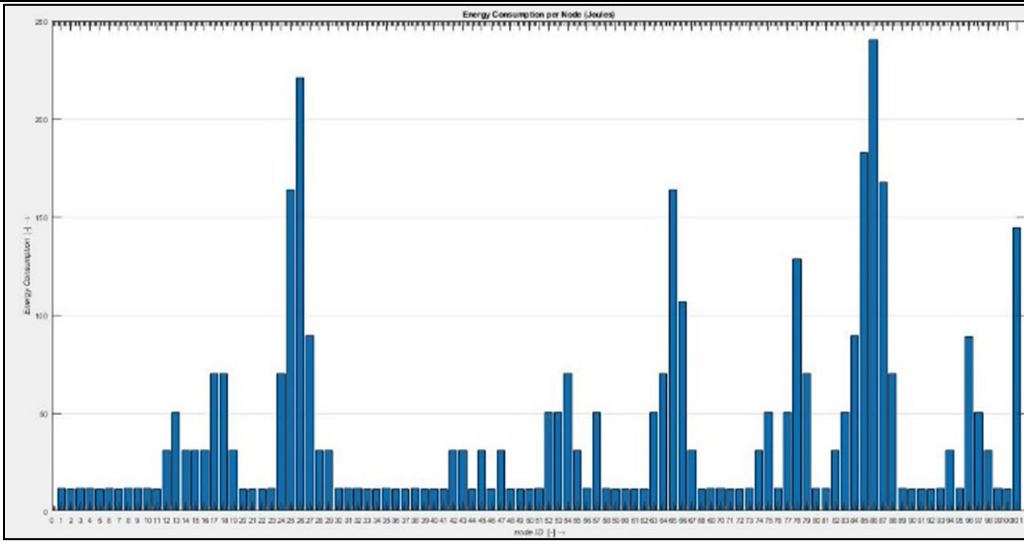

Figure 9: Energy Consumption per node as per scenario 4.

Scenario 5 (S5):

In the fifth scenario, the cluster heads (CHs) were positioned at the center of their respective clusters, which reduced the hop count between the source and CHs. This configuration resulted in fewer intermediate nodes compared to Scenario 3, as the topology includes a total of six CHs. The selected CHs are nodes 13, 18, 43, 48, 73, and 78, as shown in Figure 5(d). Energy consumption per node is presented in Figure 10. The source node selection and the communication between CHs and the sink follow the same approach as in Scenario 4. The results in Figure 10 indicate that all nodes consumed less than 100 joules, excluding CHs. This demonstrates a significant reduction in both per-node and collective energy consumption. The total energy saved is 62.279% compared to Scenario 1, as detailed in Table 4.

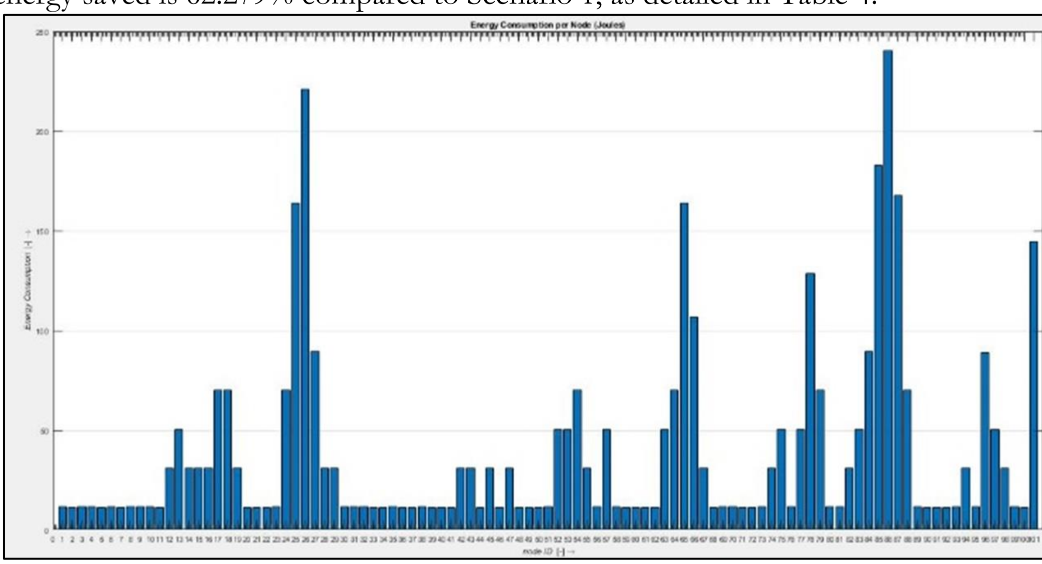

Figure 10: Energy Consumption per node as per scenario 5.

Figure 11 presents the comparative results, showing reductions of 34.836%, 20.11%, and 26.05% in energy consumption compared to Scenarios 2, 3, and 4, respectively. These results are further detailed in Table 4, where the energy used in Scenario 1 is used as a reference for the total energy consumed (TE) to calculate energy savings in the other scenarios. The CH-AODV protocol effectively optimizes hop count, reduces wasteful energy consumption, and utilizes clustering to enhance overall network performance. These findings can inform further research and practical implementations in wireless sensor networks (WSNs).

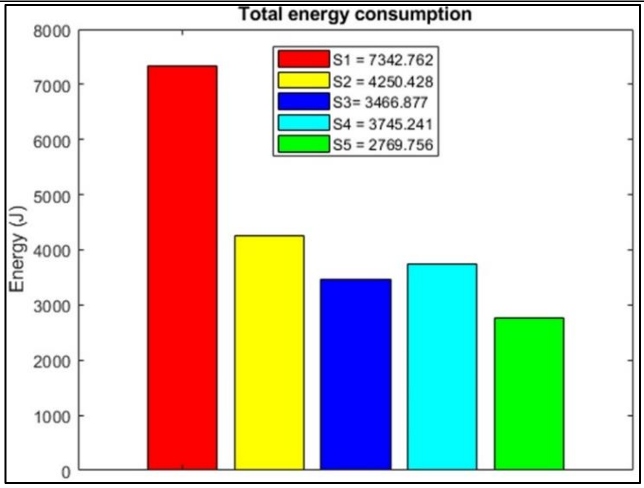

Figure 11: Accumulated energy consumption of all scenarios.

Conclusion:

In this paper, we investigated energy consumption in wireless sensor networks (WSNs) by simulating the Ad hoc On-Demand Distance Vector (AODV) routing protocol, a shortest path algorithm, and clustering techniques using MATLAB. Five scenarios were analyzed, each employing a multihop approach and a grid formation. Each scenario was simulated for 30 seconds, with approximately 60 transmissions performed. The results demonstrate that a higher number of hops between the source and destination leads to increased energy consumption in sensing, transmitting, and receiving data. Conversely, the cluster head (CH) technique significantly reduces energy consumption by minimizing the number of intermediate nodes between the source and CHs. Centralized CHs within the cluster further enhance energy savings by reducing the number of hops compared to edge-based CHs.

While cluster-based routing offers benefits in WSNs, there are potential drawbacks to consider:

Uneven Energy Consumption: CHs handle more tasks, such as data aggregation and forwarding, leading to faster energy depletion compared to regular sensor nodes. This can create energy holes and shorten network lifetime. If a CH fails, the entire cluster may lose connectivity. Redundancy mechanisms or dynamic CH selection can help address this issue.

Communication Overhead: The process of electing CHs and forming clusters can introduce communication overhead, particularly in protocols with frequent re-clustering. Some CH selection algorithms may not scale well with very large networks, requiring more complex calculations or communication.

Cluster Formation Instability: Frequent movement of sensor nodes can disrupt cluster formations, necessitating more frequent re-clustering and potentially impacting network stability.

These challenges are actively researched, with various techniques being developed to mitigate them. For example, protocols are being designed to consider remaining energy for CH selection, implement backup CHs, and optimize cluster formation to reduce overhead.

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Conflict of Interest: There are no conflicts of interest.

Glossary:

Term	Definition
AODV	Ad Hoc On-Demand Distance Vector
BS	Base stations

CH	Cluster head
CH-AODV	Cluster head-based AODV
CHS	Cluster Head Selection
C3HA	Cluster-Centered Cluster Head Selection Algorithm
EECHIGWO	Energy-efficient cluster head selection using an improved version of the gray wolf optimization
LEACH	Clustering algorithm
LEACH-EP	Energy prediction LEACH
WSN	Wireless Sensor Networks

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