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Original Article

GEDIR-MST: Geographic Routing Enhanced By Minimum Spanning Tree for Efficient Data Transmission in Wireless Sensor Networks

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Abstract - *Wireless Sensor Networks (WSN) are decentralized networks of autonomous sensor nodes equipped with sensing, processing and communication capabilities. Geographic Routing Enhanced by Minimum Spanning Tree is a novel routing algorithm specifically designed for WSNs. This algorithm integrates the principles of geographic routing with the construction of a Minimum Spanning Tree (MST) to enhance data transmission efficiency within the network. The process begins with networks' initialization, where the sensor nodes are deployed and assigned unique IDs and geographic coordinates. Data transmission uses the Geographic Distance Routing GEDIR method, whereby each node chooses the neighbour geographically near the target. Simultaneously, a distributed algorithm constructs a Minimum Spanning Tree, ensuring the minimal total edge weight and optimizing factors like communication cost and energy consumption. MST is the backbone of routing path determination in which the nodes navigate through a tree using geographic routing principles to reach the destination efficiently. The combination of GEDIR and MST in GEDIR-MST Routing aims to significantly improve routing efficiency, reduce energy consumption, and enhance the overall network performance in WSN.*

Keywords - *Data Transmission, Geographic Routing, Minimum Spanning Tree, Network Initialization, Wireless Sensor Networks.*

1. Introduction

Many real-world applications exist for Wireless Sensor Networks (WSNs), including healthcare, pollution monitoring, target tracking, defect detection and environmental measurement [1]. The primary component of each node is an antenna-equipped radio transceiver, a microprocessor, and some energy supply. Normally, a small battery is not easy to recharge or replace due to the harsh and rejected environment, which limits the energy capacity in long-term deployment [2].

An essential part of any WSN is the routing process, which governs the discovery of routes and effective delivery of data from beginning to end, regardless of the path states between. Researchers and businesses have developed many routing protocols that aim to reduce power consumption and extend network life [3, 4]. The primary difficulties of WSN routing protocols are energy consumption, deployment of nodes, scalability, connection, coverage and security [5]. Numerous industries and sectors extensively use WSNs for various purposes, such as agriculture, environmental monitoring, healthcare, transportation, catastrophe prediction, and the military [6]. These little sensors have improved people's lives. In other instances, production has significantly reduced the downtime and associated expenses in different kinds of equipment [7, 8]. Using sensor detection, procession, and communication capabilities is crucial [9]. Also, the limited power source greatly affects the performance of WSNs, including the transceiver, memory, and central processing unit [10]. Thus, fixing the shortcomings is the only solution to this issue, which boosts the efficiency of WSNs and increases the lifespan [11, 12].

Enhancing energy efficiency, increasing network communication, extending network lifetime and minimizing latency are the driving forces for creating the clustering strategy [13] using pre-defined criteria and clusters, which refers to clustering a group's nodes into sets. These criteria include providing Quality of Service (QoS), lowering the resource utilization and accomplishing the network load balancing [14, 15]. Following that, one node is selected for each cluster to function as the Cluster Head (CH). Carrying out data aggregation and fusion, the CH is in charge of combined shifting and fused data from the sensors in the same cluster to the Base Station (BS) [16]. Choosing the right person to lead each cluster is critical for the network energy efficiency and transmission latency [17].

The main donation of the work is:

- Network Initialization
- Geographic Routing
- Minimum Spanning Tree (MST) Construction
- Routing Path Determination

The remainder of this paper is organized as follows. Section 2 discusses the different Geographic Routing techniques. Section 3 debates the GEDIR-MST model. Section 4 debates the findings of the study. Section 5 ends with the debate of findings and proposals for further findings.

1.1. Motivation of the Paper

The motivation behind Geographic Distance Routing Enhanced by Minimum Spanning Tree (GEDIR-MST) lies in addressing the key challenges that Wireless Sensor Networks face. These challenges include inefficient routing methods, high energy consumption and suboptimal network performance. By integrating geographic routing principles with MST construction, GEDIR-MST aims to improve routing efficiency by selecting the optimal paths based on geographic proximity, thus reducing communication costs and energy consumption. The algorithm aims to improve network performance and sustainability, a promising solution for WSNs operating in resource-constrained environments.

1.2. Research Gap

Since standard MST is based on consistent configuration, adapting GEDIR-MST to networks with mobile or often changing nodes is problematic. The computational cost of creating MSTs has the chance to rise. Hence, addressing the scalability of GEDIR-MST in bigger WSNs is overlooked. Combining GEDIR-MST with security procedures helps in the battle against Gray-Hole and Black-Hole Attacks, which disable the networks. If these issues are resolved, the flexibility and resilience of GEDIR-MST's efficiency in diverse WSN contexts will be significantly improved.

1.3. Novelty of Work Compared to the Existing Methods

Combining Geographic Distance Routing (GEDIR) with Minimum Spanning Tree (MST) ideas yields the GEDIR-MST Routing algorithm, which has significant advantages over existing WSN routing approaches. Unlike the traditional geographic routing systems, which result in redundant transmissions and loops, GEDIR-MST maximizes energy usage by minimizing communication costs via the MST backbone. Although GEDIR's MST design ensures efficient and loop-free paths, the proximity-based approach further reduces transmission delays and energy consumption. GEDIR-MST is a steady and adaptable WSN system that improves routing reliability, network longevity, and network state adaptation over pure MST or geographic routing principles.

2. Background Study

D, R., and Chaudhari, S. [1] Multipath routing has been a popular topic in WSN in response to increased concerns about network latency, reliability, throughput, load balancing and longevity. Those improvements in WSN immediately resulted in greater demand for continuous data transfer across many channels. Starting Multipath routing systems sparked a lot of curiosity. Multipath routing increased the WSN performance by expanding and offering multiple options in each category.

Dagdeviren, Z. A [2] MSP-based Clustering and Backbone Formation Algorithm (MICUB) technique had been offered for WSNs based on the notion of MSP building. MICUB generated the sensor node cluster and backbone information using inputs such as transmission range, node placements, sensing area dimensions and division values. Starting with a minimum spanning tree backbone, the approach allowed communication across clusters. Following that, the program clustered the network, appointed an administrator to every cluster, and established the connections inside every cluster using the least Spanning Tree approach. The number of different numbers in the proposed approach was compared to that of their competitors to improve the clustering quality.

Hao, K.et al. [3] Unified Wireless Sensor Networks had two main problems: localization and routing. Here, the author presented Energy Efficient Localization (EEL), a new routing technique for Underwater Wireless Sensor Networks (UWSNs) that considered the precise locations of individual nodes. When designing the routing protocol, the author considered both factors in light of three-dimensional dynamic UWSNs.

Huang H.et al. [5] the author created and explored Energy-efficient Multicast Geographic Routing (EMGR), a destination-driven multicast geographic routing system designed for usage in WSNs with limited resources. EMGR allowed the multicast message delivery by using an energy-aware destination-driven multicast tree. EMGR was the optimal solution; this method was quick, simple, and scalable. EMGR excelled in three areas in accordance with the theoretical analysis: guaranteed delivery, computer complexity, and packaging of the encapsulation overhead.

Jin, R., [6] Using multi-hop transmission and fusion extended the lifespan of WSN, reduced the duplicate data exchanges and saved the energy on sensor nodes. These authors compared relay and non-relay transmission regarding energy use and then developed a model for optimum relay cost, determining which relay nodes were most cost-effective. The network and relay nodes were designed such that energy dissipation during the transmission was minimized using the multiple setups of the minimum spanning forest technique. To offer multiple-hop propagation with data compiled, reduced data collisions, and maximized node sleep duration in the non-working state, we changed the TDMA cycle and developed a bottom side with a time slot assignment mechanism. All of the cluster heads were able to synchronize the data transmitting frequencies with the least delay during the inter-cluster transmission stage, which allowed them to sleep well in case they did not work.

Li, Y., [8] Applying the Spanning Tree issue to gather data and disseminate it in industrial WSN provided the theoretical framework for understanding these networks. Conventional procedures such as the Kruskal and Prim algorithms yielded only one answer at a time. To increase the dependability, factory application settings provided several mutual backup options. Depending on the concept of quantum computing, the Spanning Tree building technique for factory WSN was offered as an improvement over the artificial bee colony approach.

Lima, M.et al. [9], described in this work, stated that those authors' novel geographic routing method, REACT, collected the data and avoided the routing holes. Those authors' methods relied on the sink node in having a powerful communication device that reached each node in the network with only one hop. Utilizing the nodes' RSSI values, those authors' solutions introduced a novel packet forwarding method that combined the data and self-selected the next hop candidates to avoid the routing holes.

Messous S. et al. [11] those authors research presented a new methodology for multiple-hop WSN packet routing that was both highly efficient and less power-hungry. Data was routed from each sensor node to the drop node using the notion of MST, which is based on the minimum hop counter used in the suggested technique. The author thought of WSN as a group of static nodes that had spread out in the unknown square field at random. Matlab was used to implement the suggested methodology. The following variations in routing metrics were applied to the same network topology: minimum hop count and geometric distances between nodes.

Pandith, M.et al. [13] Geographic Routing Protocols (GRP) in WSN were the subject of this paper's survey. The study also covered the routing maintenance table built using GRP methods, including Face-2 routing algorithms and greedy forwarding. The author concluded the routing techniques after analyzing numerous schemes and the structure of topological networks.

Sana, M. et al. [15] the article discussed the multi-hop wireless sensor network routing strategy. The technique depended on the MST idea, which worked well in isotropic and anisotropic utilizing zones. The hop counter allowed the count of the hops needed to transfer the data from nodes to the sink. WSN had been evaluated with several randomly distributed sensor nodes in a sensing square field. All the simulations were performed using MATLAB 2015a. When creating the trees, a variety of routing criteria, such as the minimum hop count and node distances, were applied. This application demonstrated the route optimization performance technique using two routing metrics. Simulation findings showed that the minimal hop-routing outperformed the distance-based routing in terms of reducing every sensor node connected in the data packet transmission.

Sangaiah, A. K et al. [16], in several WSN routing systems, the starting node transmitted the route requirement. The data was subsequently transported from beginning to end using the network's chosen route and the appropriate protocol. This paper adopted the different route search approach. The major contribution of this article was to provide a default routing tree for usage in network operations. A preset tree was used to reduce the overhead communication. The network computed and stored the relay ability, a metric that spanned the sink to the border node. When the node had data to send to the sink, the computed values discussed earlier were used to choose the best path. Despite the increased network latency, the suggested method allowed the appropriate monitoring of data in the domain of health monitoring. Selecting the suitable topology resulted in increased efficiency. The target tracking situations and coverage were evaluated using the test network simulation.

Sridhar, M., and Pankajavalli, P. B. [17] For k-coverage energy hole identification and relief in WSN, this research proposed the optimal distributed cooperation method with Energy-Aware Dual-Path GR (EDGR) that reduced the Delivery Delay (DD). Initially, the nodes worked together to identify and recover from the energy holes using the Optimized Distributed Voronoi-based Collaboration (ODVOC)-EDGR approach. This technique built the Local Voronoi Diagrams (LVDs) and allowed the nodes to monitor each other's vital position in their immediate vicinity. In addition, the author provided the ODVOC-EDGR protocol that found the globally optimum routes for DD reduction using the Intelligent Water Drop (IWD) method.

2.1. Problem Definition

Geographic Distance Routing Enhanced by Minimum Spanning Tree (GEDIR-MST) addresses the inefficiencies and underperformance of traditional routing approaches in Wireless Sensor Networks (WSNs). High energy usage, communication costs and inadequate routing patterns contribute to these networks' reduced efficiency and performance. GEDIR-MST aims to overcome these challenges by merging the geographic routing theories with MST architecture, optimizing the data transmission lines, cutting energy usage and improving the overall network performance in WSNs.

3. Materials and Methods

This section looks for the components and techniques for utilizing the GEDIR-MST Routing system of WSNs. This paper proposes a unique strategy for increasing the data transmission efficiency in WSNs by integrating Geographic Distance Routing (GEDIR) and Minimum Spanning Tree (MST). Combining the capabilities of two ways makes WSN routing systems capable of dealing with common problems and using the benefits of both approaches. To properly highlight the various advantages of the GEDIR-MST strategy, including the comprehensive comparison with existing routing systems, a few key elements like scalability, energy economy, routing dependability and response to changing network circumstances were considered in this comparison. The article demonstrated the improvement of the proposed algorithm on existing solutions by comparing GEDIR-MST to the standard geographic routing, MST-based protocols and hybrid techniques. This underlines the technique's unique benefits and potential impact on WSN performance. This part of the paper issues the complete summary of methodologies used in evaluating the performance and function of the initiate routing algorithm.

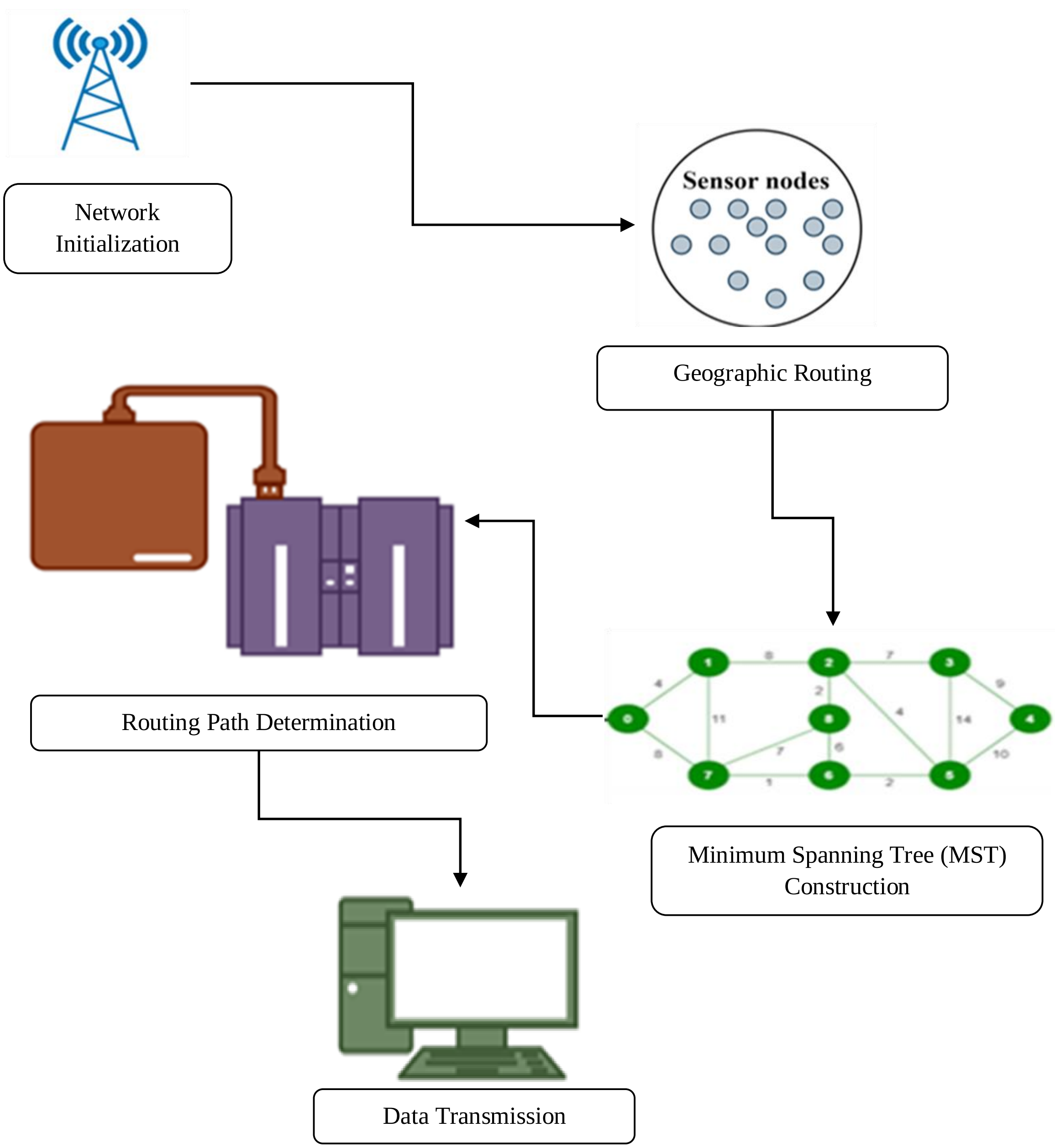

Fig. 1 GEDIR-MST workflow architecture

3.1. Network Model

The network model in GEDIR-MST Routing includes the arrangement and connectivity of sensor nodes within the Wireless Sensor Network (WSN). This network includes the parameters such as the total number of sensor nodes(N), the source node (S_i) for data transmission, the destination node (D) and set of edges (E) represents the communication link between the nodes. Additionally, the model incorporates a cost function $c(u, v)$ to calculate the geographic distance between nodes u and v, allowing efficient routing based on spatial proximity.

In Equation (1), the Geographic distance between the two nodes u and v are calculated using the Euclidean distance formula:

$$c(u,v) = \sqrt{(x_u - x_v)^2 + (y_u - y_v)^2} \quad (1)$$

Where:

- (x_u, y_u)And(x_v, y_v) are the geographic coordinates of nodes u and v, respectively.

This formula calculates the straight-line distance between two nodes based on their geographic positions.

In the GEDIR-MST Routing algorithm, nodes use the calculated geographic distance to determine the nearest neighbour towards the ending node during the routing process. The MST construction algorithm ensures efficient connectivity among all the nodes while minimizing the overall communication cost or energy consumption.

3.2. Geographic Routing

Location data and the other mobility factors supplied by positioning devices like GPS are the backbone of geographic routing. With each iteration, these routing protocols aim to decrease the geographical distance to the target node.

The growing availability of Node Navigation Systems (NSs) has boosted the geographic routing techniques for vehicular networks. NS includes the hardware for locating the user (usually a GPS), a database of routes with various pieces of information, and so on. This mountain of data allows making educated guesses about when data goes to a certain destination node.

Even though there are a number of geographic routing protocols, most of the protocols suggested for node communications cannot work in sparse (low node density) situations. For instance, VANETs' position-based routing algorithms described are not steady enough to handle long-term disruptions, intermittency or frequent network partitions. Hence, this is suitable for Vehicular Delay Tolerant Networks (VDTNs).

The forward routing algorithm GeOpps determines the routing options and stores only one copy of each network bundle. Next, the navigation system determines the Enterprise Technology Architecture (ETA) necessary to get from NP to D and ETA to NP for the car. The Minimal Expected Time of Delivery (METD) is a utility function used to determine the routing choices; this is the sum of these values and is indicated in Equation (2).

$$METD = ETAtoNP + ETAfromNPtoD \quad (2)$$

Nodes only advance a bundle when the encountered node's METD exceeds the present carrier's METD. If this is the case, the encountered node is probably heading toward the bundle's destination either closer or quicker. The procedure is repeated when the bundle's time-to-live expires or reaches the destination.

The GEDIR-MST approach often uses Global Navigation Satellite Systems (GNSS) or localized positioning systems such as Zigbee or Ultra-Wideband (UWB) to determine the geographic coordinates. These systems allow the sensor nodes to receive signals from satellites or nearby anchors to determine their location. The precision of these coordinates influences the routing effectiveness because nodes pick a route based on their proximity to the destination utilizing accurate geographic information. Conversely, incorrect coordinate collection results in less-than-ideal routing pathways with increased energy consumption and longer data transmission delays. A node's poor location estimates the result in a long, more energy-intensive route and chooses the inefficient neighbor for packet forwarding. Furthermore, if the nodes are often changing and the position data is incorrect, the network is forced to recalculate the pathways frequently using more resources. Thus, improving the routing effectiveness of the GEDIR-MST protocol in WSNs requires adequate coordinate collection and high spatial accuracy.

3.3. Route Request

Source nodes in networks typically search the route to a destination node using routing techniques such as AODV or DSR. The starting node first transmits a packet to the destination carrying the route information.

The packet is then sent to the intermediary node either knowing the route or the final end. Using formulae like NextHop(D) = Neighbor(D) helps to find the quickest path or next hop depending on the hop count or quality of service. With this approach, the network nodes find the best data distribution method, as shown in Equation (3).

$$NextHop(D) = Neighbor(D) \quad (3)$$

Where (D) is the nearest node with the shortest route to ending node D.

3.3.1. Route Reply

In networking, the route reply is a critical response that provides the starting node with critical path data to reach the destination. This begins with route requests. This sequence is critical for establishing effective communication pathways in ever-changing network setups. The originating node first sends an RREQ packet to locate the ending node. The RREQ packet moves forward across the network, eventually arriving at the intermediate nodes. An intermediate node replies to a request instantly or chooses to transmit after determining the route to the end. A Route Reply (RREP) is sent back to the starting node when a node arrives with a valid path. This completes the route-finding phase and ensures a successful network connection. In Equation (4), the Reply probability is calculated as follows:

$$Replyprobability = \frac{RemainingEnergy}{rotalenergr} \times QoSFactor \quad (4)$$

3.4. Minimum Spanning Tree (MST) Construction

The MST in GEDIR-MST technology is designed to dynamically alter the network topology. Initially, depending on the geographic distance and energy costs, the MST is built using a distributed approach such as Prim or Kruskal. The MST moves locally to reduce the disruption caused by network changes such as node mobility, failures and additions. Only the affected edges are calculated for the node movements; node failures trigger a local repair mechanism that rejoins the partitions. New nodes are considered as they improve the existing tree design. Periodic optimization ensures that the MST remains efficient without needing a full rebuild by balancing the efficiency and computational costs.

The MST problem is a graph problem; one way to solve it is by using input graph G to generate the 1-ANT. In reality, there are two directed edges in each undirected edge$\{a, b\}$, which are $(a, b)$and(a, b). However, the transformation of an ant's random walk on G into a Spanning Tree is not immediately clear. This is interesting to note that the renowned method Broder developed is a random walk algorithm. This algorithm selects from all the spanning trees of G evenly and randomly. Under the premise that the MST problem is considered, the heuristic information $\eta\{a, b\}$ of an edge $\{a, b\}$ in G is inverse of the edge's weight. The parameters αandβ, related to pheromone levels, govern the range of used heuristic data.

The created Spanning Tree T is used to update the pheromone values τ when the new solution has been approved. A frequent method to ensure convergence is to keep the upper and lower limits on these variables. This was also advised in the prior runtime examination of MST. Based on the assumptions, the τ-value of every corner in the construction graph eventually approaches either the upper limit h or the lower limit after each update. This means that after the update, given the new pheromone values τ 0, then

$$\tau_{\{u,v\}} = hif\{a, b\}\epsilon T and \tau_{\{u,v\}} = lif\{a, b\}\epsilon T. \quad (5)$$

Because a very big number causes the tree to undergo several modifications in the next phases, and a very large value for h makes such changes improbable, the ratio of these two factors is critical.

First, consider the Broder-based construction graph with $\alpha = 1$and$\beta = 0$. The results of this are as follows. Assume that u is the present node in the random walk and R be the total of all pheromone values of edges that intersect with u and are denoted as$P \{a, b\} \in E\tau\{a, b\}$.

Referring to the configuration of α, β and h, the cubic update scheme is used for simplicity. To learn more, the following basic estimates of the crossing probabilities are calculated from the pheromone values. Consider the node v with i edges of value and $k$edges of value$h$, whereas $h = n\,3$' and$k + i < n - 1$. In Equation (6), the odds of selecting an edge with a value of h are as follows:

$$\frac{kh}{kh+il} = 1 - \frac{i}{kn^3+i} \geq -\frac{1}{n^2} \quad (6)$$

Where one edge with a value of h is randomly selected from the set of all edges, picking the edge with a value of is likely to happen at least once.

$$\frac{l}{l+(n-2)h} \geq \frac{l}{nh} \geq \frac{1}{n^4} \quad (7)$$

The following theorem proves that MST in the above scenario creates MSTs in the predicted polynomial time, given that w_{max} is the greatest edge weight, and it is not too big.

3.5. Routing Path Determination

After the Minimum Spanning Tree (MST) has been constructed in the network, the Routing Path Determination phase focuses on establishing the efficient path from the Source node (S_i) to the end node (D). This process utilizes the structure of MST to guide the data packets through the network while continuing the geographic routing principles.

3.5.1. MST Utilization

The Source node(S_i) utilizes the connectivity provided by MST to determine the routing path towards the destination node (D). The MST ensures that all the sensor nodes are interconnected with minimal edge weights, which is an optimized backbone for routing decisions.

3.5.2. Geographic Routing Principles

While traversing the MST, the source node $S_i$applies the geographic routing principles to select the edges that lead closer to the destination node$D$. This involves considering the geographic coordinates of nodes to make informed decisions about the next hop in the routing path.

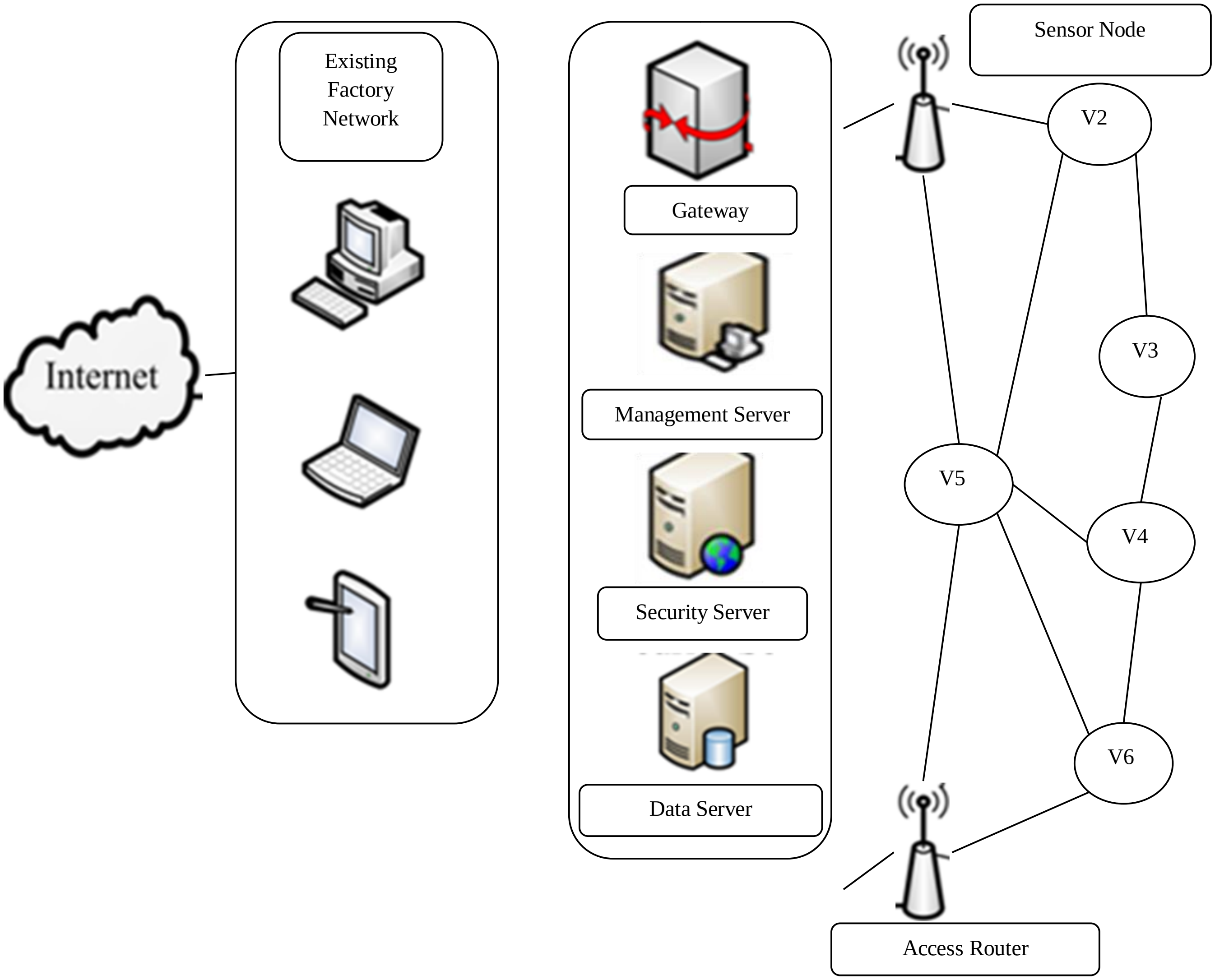

Fig. 2 Minimum spanning tree

3.5.3. Path Selection

The routing path is determined by selecting the edges within MST that progressively approach the ending node D based on the geographic proximity.

This path selection process aims to minimize the distance travelled by data packets and optimize the routing efficiency within the network.

3.5.4. Efficient Data Forwarding

Once the routing path has been established within the MST, data packets originating from S_i are forwarded through the selected edges towards the ending node D. Each intermediate node in the path forwards the packets to the next hop based on the geographic coordinates, ensuring a streamlined and energy-efficient data transmission process.

Algorithm 1: GEDIR-MST
Input: Graph G representing the network topology(V, E). Geographic coordinates (x_u, y_u) for each node$u \in V$. Source node S_i and ending node$D$. Parametersα, β, h, `controlling pheromone values and heuristic information. Steps: Initialize pheromone values τ and heuristic information η for all the edges in graph$G$. Construct MST T using α, β, h, and a. Calculate the heuristic information $\eta\{u, v\}$ as the inverse of the weight of edge $\{u, v\}$ in$G$.

$$\frac{kh}{kh+il} = 1 - \frac{i}{kn^3+i} \geq -\frac{1}{n^2}$$

b. Perform to select the edges proportionally based on pheromone valuesτ.

c. Update pheromone values τ based on the constructed spanning tree T.

d. Maintain upper and lower bounds on pheromone values for convergence.

Utilize MST T for routing the path determination:

a. Start from the source node S_i and traverse MST T towards the destination node$D$.

$$\frac{l}{l+(n-2)h} \geq \frac{l}{nh} \geq \frac{1}{n^4}$$

b. Apply the geographic routing principles to select the edges that lead closer to$D$.

c. Determine the routing path within MST T by progressive approaching$D$.

Forward the data packets from S_i to D along the established routing path in MSTT:

a. Each intermediate node forwards packets to the next hop based on coordinates.

b. Ensure streamlined and energy-efficient data transmission process.

Output:

Routing path from S_i to D within the Minimum Spanning Tree (MST)T.

Efficient forwarding of data packets from S_i to D along the established routing path.

4. Results and Discussion

The results and discussion section analyzes and interprets the outcomes obtained from implementing the GEDIR-MST Routing algorithm in Wireless Sensor Networks (WSNs).

This section highlights the performance metrics, compares them with existing methods (EMGR and REACT), and provides insights into the algorithm's effectiveness in improving routing efficiency, reducing energy consumption, and increasing overall network performance.

Key metrics such as throughput levels, routing efficiency, energy levels, and PDR are explored to calculate the performance of GEDIR-MST Routing and the advantages of EMGR and REACT in WSNs.

The proposed GEDIR-MST performed well compared to the other existing algorithms. Examining the data to see the pairing of spatial routing with MST increases the WSN performance. Discuss any identified trade-offs, such as processing overhead during MST updates and provide solutions to these issues. This extensive analysis proves the GEDIR-MST method's effectiveness in various WSN scenarios and highlights the advantages over traditional techniques.

4.1. Challenges Related to Energy Consumption

WSNs rely heavily on energy consumption as the sensor nodes have limited power. The objective is to minimize the total energy consumption across all the network nodes.

$$\sum_{b\in N(a)} E_{a,b} \cdot x_{a,b} \leq E_a^{init}, \ \forall a \in V \qquad (8)$$

$E_{a,b}$ Represents the energy consumed for data transmission from node a to node b, and V is the set of all nodes in the network. Where N (a) is the set of neighbours of node a, and $x_{a,b}$ is a binary variable indicating whether a link between nodes a and b is active ($x_{a,b}$=1) or not ($x_{a,b}$=0), initial energyE_a^{init}.

4.2. Challenges Related to Communication Cost

In WSNs, communication cost refers to the expenditure of resources (typically electricity) required for data transmission. Typically, the distance between the nodes and the amount of data delivered influence this cost.

$$C_{total} = \sum_{a\epsilon V} \sum_{b\epsilon N(a)} c(a,b) \cdot x_{a,b} \qquad (9)$$

$$C\ (a,\ b) = \alpha \cdot d\ (a,\ b)$$

Let d (a, b) represent the distance between the nodes a and b, and α is the constant reflecting energy expenditure per unit distance. The communication cost c (a, b) for each link between the nodes a and b, the total communication costC_{total}.

4.3. Challenges Related to Network Performance

Network performance in WSNs is often measured in terms of route dependability, Packet Delivery Ratio (PDR) and latency. Here, the focus is on latency, which has a direct impact on data flow efficiency.

$$T_{total}(R) = \sum_{(i,j)\in R} t_{a,b} \cdot x_{a.b} \qquad (10)$$

Let $t_{a,b}$ be the latency between nodes a and b. The total network latency T_{total} for a specific route, RRR is calculated from the source node s to a destination node d. where $(i,j) \in R$ represents the links along the chosen route R.

$$\text{Throughput}=\frac{NumberofPacketSize}{Timeduration*SuccessfulaveragePacketsize} \qquad (11)$$

Table 1. Throughput comparison chart

	Throughput Levels		
Packet Size	**EMGR**	**REACT**	**GEDIR-MST**
50	0.476	0.588	0.625
100	0.952	1.176	1.25
150	1.428	1.764	1.875
200	1.904	2.352	2.5
250	2.381	2.941	3.125

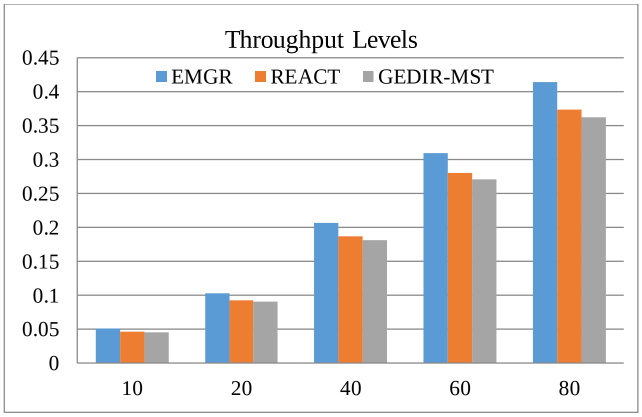

Fig. 3 Throughput comparison chart

Table 1 and Figure 3 data represent the Comparison of Throughput levels for three systems (EMGR, REACT and GEDIR-MST) at varying packet sizes. Throughput is the rate at which the data is effectively transferred via the system. Looking at the values provided, the packet size increases from 50 to 250, and all systems have a consistent trend of growing throughput. For instance, EMGR shows a Throughput value of 0.476 at a packet size of 50, which rises to 2.381 at 250. Similarly, REACT's Throughput increases from 0.588 to 2.941, and GEDIR-MST's Throughput rises from 0.625 to 3.125. This trend suggests that the larger packet sizes generally result in higher throughput across these systems, indicating the ability to handle the larger volumes of data more efficiently.

Traditional geographic routing algorithms often chose routes based on proximity, resulting in less-than-ideal pathways over time and higher energy use. The GEDIR-MST technique decreases by using an MST backbone, which minimizes the total number of edge weights—that is, transmission energy or distance—over the network. This ensures the channels with the least cumulative energy consumption guide the data transport. In the investigations, MST-guided selection significantly reduced the duplicated transmissions, prolonging the node lifespan and increasing the overall network lifetime.

$$\text{Energy}=\frac{Number of Sensor nodes}{Energy consumption for sending packets at a times} x\ 100 \quad (12)$$

Table 2. Energy comparison table

	The Energy Level in Joules		
Number of Nodes	**EMGR**	**REACT**	**GEDIR-MST**
10	58	47.6	43
20	117	95	86.9
40	235	190	173.9
60	352.9	285.7	260.8
80	470.5	380.9	347
100	588	476	434.7

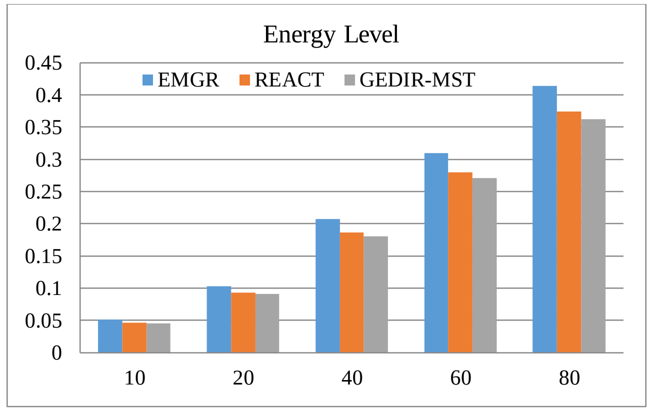

Fig. 4 Energy Comparison Chart

Table 2 and Figure 4 data present the energy levels in joules for three systems (EMGR, REACT and GEDIR-MST) across the varying numbers of nodes. Energy level refers to the energy consumed or required by a system or network. Analyzing the values, it is evident that as the number of nodes increases from 10 to 100, there is a consistent pattern of increasing energy consumption for all the systems. EMGR, for example, has energy levels that range from 58 joules with 10 nodes to 589 with 100 nodes. Similarly, the energy consumption of REACT increases from 47.6 to 476, whereas GEDIR-MST increases from 43 to 434.7. This trend illustrates that the energy needed by these systems rises proportionally with the network size—that is, the number of nodes—suggesting the need for appropriate energy management measures as the network develops. Unlike more conventional approaches, the GEDIR-MST technology ensures consistent data transport while reducing the latency. The MST backbone assures that the paths are loop-free and efficient in lowering both hop count and duration. On the other hand, proximity-based GEDIR routing prioritizes the nearest available node to improve reliability and speed. This has resulted in lower end-to-end delays and higher PDR in performance measurements than the benchmarks that prioritize latency or energy.

$$\text{TimeDelay} =\frac{Number of Sensor nodes}{packet\ send\ energy\ consumption\ time \times forwarding\ time\ in\ ms} \quad (13)$$

Table 3. Time delay comparison table

	End-to-End Delay (ms)		
Number of Nodes	**EMGR**	**REACT**	**GEDIR-MST**
10	0.051	0.046	0.045
20	0.103	0.093	0.091
40	0.207	0.187	0.181
60	0.310	0.280	0.271
80	0.414	0.374	0.362
100	0.518	0.468	0.452

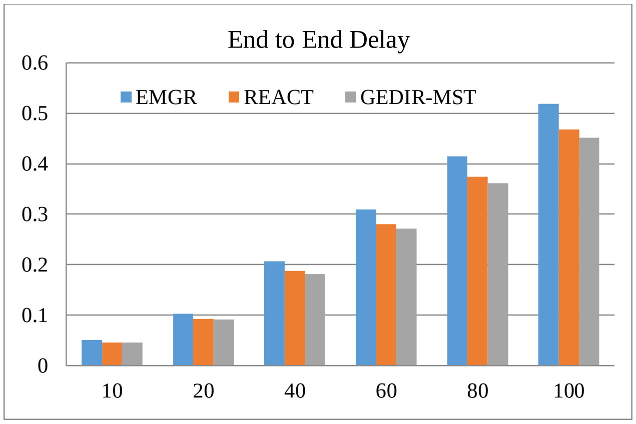

Fig. 5 Time delay comparison chart

Data in Table 3 and Figure 5 demonstrate a Comparison of Time Delays in milliseconds for the three systems (EMGR, REACT, and GEDIR-MST) with varied node counts. End-to-end Time Delay refers to the amount of time taking a packet or piece of data to travel across the network from start to end. The analysis shows a clear trend of increasing time delay for all the systems as the number of nodes increases from 10 to 100. EMGR, for example, displays Time Delays ranging from 0.051 milliseconds with ten nodes to 0.518 milliseconds with 100 nodes. Similarly, the Time Delay of REACT increases from 0.046 to 0.468 milliseconds and that of GEDIR-MST from 0.045 to 0.452 milliseconds. This suggests that larger networks with more nodes are more likely to have longer end-to-end time delays, which impact the overall performance and efficiency of data transmission in these systems.

4.3.1. Packet Delivery Ratio

Modern approaches struggle with network scalability and dynamic topologies due to the likelihood of node failure or relocation, which disrupts the routing. The GEDIR-MST algorithm's two-pronged strategy allows it to perform effectively in these scenarios. The MST architecture provides a resilient and loop-free routing backbone; the GEDIR component continuously routes the data to the nearest nodes based on real-time geographic changes. This flexibility increases the Packet Delivery Ratios (PDR) and reduces the latency by allowing the data packets to naturally move across the channels in response to the network conditions.

$$PDR= \frac{NumberofPacketsReceive}{TotalPackets} * 100 \tag{14}$$

Table 4. Packet delivery ratio comparison table

Number of Packets	Packet Delivery Ratio		
	EMGR	**REACT**	**GEDIR -MST**
50	97.2	98.8	99.2
100	98.6	99.2	99.6
150	99	99.46	99.7
200	99.3	99.6	99.8
250	99.4	99.68	99.84

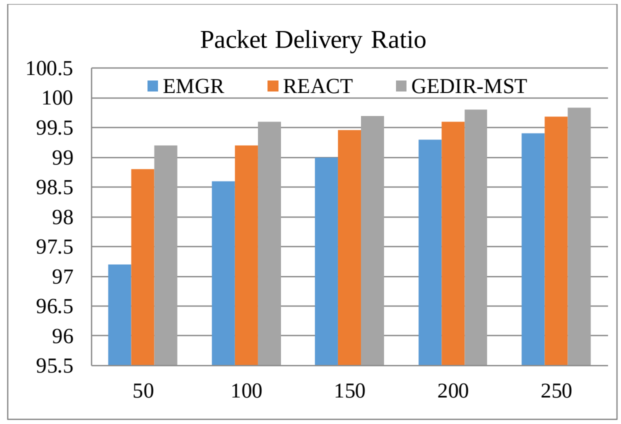

Fig. 6 Packet delivery ratio comparison chart

Table 4 and Figure 6 show the Comparisons of Packet Delivery Ratios for the three systems, EMGR, REACT and GEDIR-MST at various packet counts. A specific proportion of the deliveries are completed successfully. This is referred to as the Packet Delivery Ratio. Packet Delivery Ratio obviously improves on all the systems when the packet count grows from 50 to 250. EMGR shows the notion with PDR that ranges from 97.2% with 50 packets to 99.4% with 250 packets. REACT and GEDIR-MST delivery rates increased from 98.8% to 99.68% and 99.2% to 99.84%, respectively. These systems' packet delivery performance indicates their dependability and efficiency in the low-loss data packet transmission as their workload or the number of packets handled grows. Other data are consistent with this growing tendency.

4.4. Scalability

The GEDIR-MST technique manages networks of various sizes using spatial routing, which naturally supports local decision-making and scales efficiently with network development. In contrast, preserving the MST structure in very large-scale networks complicates the MST creation process and adds to the computer overhead. To address this problem, the MST updating process is improved for the dynamic networks, and clustering techniques are used to reduce the number of nodes involved in MST creation. This shows that the protocol continues to function effectively as the developed network results in stable performance and minimal latency.

4.5. Resilience to Security Threats

Incorporating resilience measures to combat WSN security problems such as jamming, Sybil attacks, and black-hole attacks will improve the proposed GEDIR-MST system. One solution is to provide a rudimentary authentication system that verifies the nodes' routing-related identities. The routing system includes anomaly detection technologies to further prevent the hacked nodes from interfering with the data flow. Research in reputation-based systems and cryptographic ways secure the MST generation, which assists further in increasing the protocol's resilience against hostile attacks.

5. Conclusion

Finally, the GEDIR-MST route approach provides a comprehensive solution for increasing the network performance in Wireless Sensor Networks (WSNs) via route optimization. GEDIR-MST integrates spatial routing techniques with constructing a Minimum Spanning Tree (MST) to provide effective data transfer while using less energy. Even when the MST structure decreases total edge weight and communication costs, the Geographic Distance Routing (GEDIR) ensures that the data packets follow the most efficient routes based on geographic distance. This combination strategy reduces energy consumption, which improves the routing efficiency and contributes to a highly sustainable network. GEDIR-MST Routing for WSNs shows great potential as a scalable and effective way of dealing with data transmission issues in dynamic and resource-constrained environments. Empirical numbers demonstrating the advantages of Wireless Sensor Networks (WSNs) aid the GEDIR-MST Routing algorithm's efficiency. GEDIR-MST outperforms EMGR and REACT regarding routing efficiency gains, with 0.1175 to 1.1739 vs 0.07528 to 0.7529 and 0.0607 to 0.604.

Furthermore, the energy consumption reductions, from 127 joules at 10 nodes to 1275 joules at 100 nodes, compared to EMGR's 84.3 joules to 834.3 joules and REACT's 67.6 joules to 665.6 joules, demonstrate the energy efficiency. Moreover, achieving the Packet Delivery Ratios of 98.3% to 99.66% across 50 to 250 packets surpasses EMGR's 97.2% to 99.25% and REACT's 96.54% to 99.38%. Although this has limitations, the GEDIR-MST approach significantly increases the routing efficiency in WSNs.

Depending on the accurate geographic coordinates results in performance degradation in circumstances with incorrect node placement or noisy data. Another factor impacting the scalability is the rising cost of computing the large-scale networks caused by MST development and maintenance. Future research focuses on hybrid systems that combine GEDIR-MST with Machine Learning or adaptive MST building approaches which update dynamically with the little procession or inquiry to handle the mobility better and uncertainty in the increased complex network topologies.

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