

A Smart Geographic Routing Algorithm Based on TOPSIS for Congestion Mitigation and Void Areas Bypassing in Wireless Sensor Networks

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Abstract—Wireless Sensor Networks (WSNs) are well-established, smart systems whose significance is rapidly escalating. Geographic routing offers many advantages in terms of network reliability and performance. However, they tend to fail in high congestion and the presence of energy holes. To address these challenges, a new geographic routing technique has been introduced to enhance network performance. The proposed routing algorithm is built upon the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). TOPSIS will use four criteria to forward data reports to the best-neighbor node without causing excessive congestion. In addition, the proposed algorithm will be embedded with a technique that retard the energy hole formation and can bypass them effectively without expanding them. The Path Deviation (PD) technique will prevent repetitive sending along the same paths. PD technique removes the previous forwarding node from the routing table. The proposed routing algorithm outperforms the benchmark algorithms, delivering notable improvements in packet error rate, reaching 29.3% and 16.4% compared to the FTR and EEGR algorithms, respectively. Moreover, the proposed routing algorithm demonstrates enhanced performance over the benchmark algorithms, achieving gains in packet delivery ratio of 2.6% and 1.16%, respectively. At the same time, it outperforms the network lifetime of the FTR algorithm by 28.4% and the EEGR algorithm by 11.7%. Lastly, it reduces latency by 12.2% compared with FTR and 18.2% compared with EEGR.

Keywords— geographic routing, multi-criteria decision making, path deviation, TOPSIS, wireless sensor networks

I. INTRODUCTION

Wireless Sensor Network (WSN) is the first real-world example that enabled the intelligent vision of different environmental interactions [1][2]. The importance and productivity of WSNs are derived from three key factors. Firstly, WSNs can deploy a large number of sensor nodes. These nodes can autonomously collect physical data and self-customize post-deployment. Secondly, deploying traditional wired networks is considerably more expensive than WSNs. Lastly, WSNs can adapt to dynamically changing environmental conditions. Despite their widespread use, WSNs face many open issues, including routing. Routing within WSNs is a complex task and remains a significant open

issue [3][4]. Geographic routing algorithms offer promising solutions for energy preservation, low latency, and reduced overhead [5]. Generally, remaining energy and distance are the primary criteria used in most geographic routing algorithms. These criteria identify the optimal neighboring node for forwarding data to the sink in a multi-hop communication. Even though geographic routing ensures high network performance, it still has many open issues that need improvement, offering a real opportunity to address them. For instance, geographic routing often fails in the presence of void areas or energy holes [6]. Fig. 1 illustrates the void or hole areas (energy holes), which are locations that lack sensor nodes or contain only non-functional ones, resulting in gaps in network coverage.

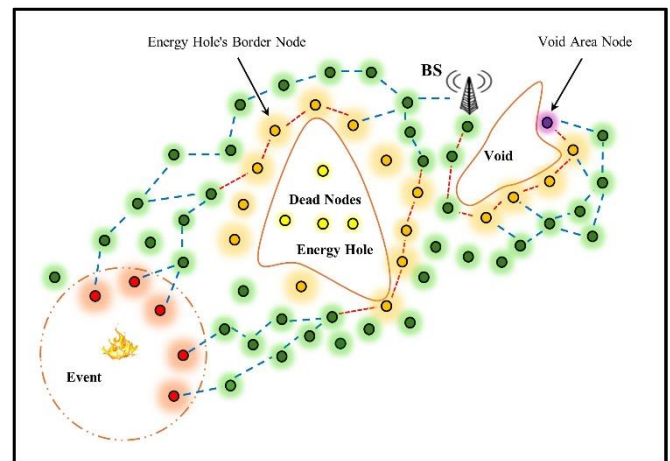


Fig. 1. Void Area in WSNs.

Energy holes within the network will appear sooner or later due to high congestion, resulting in dramatic changes in the network topology [7]. In addition, many geographic routers suffer from unbalanced workloads and congestion [8]. The main issue is that traditional geographic routing protocols rely on a single or two criteria [9]. Therefore, they cannot adaptively adjust their forwarding policy or respond to varying network conditions. This issue limits their ability to address problems such as high congestion and energy consumption.

Therefore, based on the earlier points, this work presents an enhanced geographic routing algorithm that employs a multi-criteria decision-making framework to determine the most suitable option from a set of available options. The proposed approach is based on the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS), a well-structured decision-making method for evaluating and prioritizing alternatives by considering multiple complex, often conflicting criteria. By leveraging this method, the algorithm enhances decision-making, ensuring a more efficient and reliable selection of optimal routing paths [10]. On the other hand, this work proposed a developed criterion that complements other essential criteria previously used. Predicted Buffer Occupancy (PBO) can periodically detect congestion points within the network topology due to the random locations of events. Moreover, the proposed routing algorithm will embed a developed Path Deviation (PD) technique. The PD technique can retard and bypass the energy holes. It prevents the continuous use of the shortest path. Thus, it prevents the same nodes from being overused in routing operations, thereby preserving their energy. As soon as energy holes or void areas form within the network, PD will bypass them without expanding the void area, as in previous works. As a result, this study offers the following contributions:

- The research proposes an enhanced geographic routing algorithm based on the TOPSIS method. The modified TOPSIS will use four criteria to choose the best relay node. The developed criterion is used to detect congestion inside the network. Thus, the packet error rate and packet delivery ratio will be dramatically enhanced.
- The research presents a new technique to prevent the repetitive sending along the same path to retard the formation of energy holes. Moreover, it can bypass the void area easily based on the Neighbor Information (NB-Info) table.

The remainder of this paper is structured as follows. Section II reviews related work on congestion and void-area issues along with existing solutions. Section III introduces the proposed routing algorithm. Section IV presents the simulation results and performance evaluation. Finally, Section V concludes the paper and discusses future research directions.

II. RELATED STUDIES

Previous approaches have proposed various solutions to efficiently address congestion and void-area problems in WSNs. These solutions range from congestion control mechanisms that dynamically adjust data transmission rates to geographic routing techniques that bypass void regions using alternative paths. Additionally, some studies have explored hybrid approaches that integrate load balancing with adaptive routing strategies to enhance network resilience. To establish a strong foundation for the proposed congestion mitigation and energy hole avoidance strategy, related work has been extensively analyzed, emphasizing strengths, constraints, and potential areas for improvement.

Reference [11] presented an opportunistic routing algorithm to address the void area problem. The proposed approach addresses the void problem by excluding void nodes from routing in advance. However, this method expands the holes by preventing a broad range of nodes from participating in routing.

Yarinezhad and Azizi [12] introduced an enhanced geographic routing algorithm that uses a mobile sink to optimize energy consumption and mitigate the emergence of hot spots and holes. Nonetheless, the approach is limited by the sink's frequent position changes and the need to continuously update the next-hop selection in each round.

Grover et al. [13] presented a new congestion control approach based on buffer occupancy and queue length. The data level is set based on the buffer's occupancy. However, the algorithm has high overhead due to continuous buffer occupancy checks.

Biswas and Samanta [14] introduced an innovative geographic routing algorithm that navigates around void regions by leveraging the minimum-hop-count metric, which is dynamically updated in the neighbor information table at regular intervals. However, as with right-hand-rule approaches, the void area will expand dramatically due to the continuous use of border nodes.

Marygetsy et al. [15] presented a new two-tier model for congestion control using a dynamic queue. Fuzzy logic is used to build routing decisions. The authors claimed that the proposed model is successfully used to prevent, detect, and relieve congestion. By using unequal node weights, the algorithm can enhance network lifetime. However, the proposed algorithm makes routing decisions based solely on two criteria: remaining energy and delay. Considering that only two criteria are used to construct the routing decision, it does not accurately reflect topology changes. As a result, it may not account for the actual conditions in WSNs.

Considering the limitations of the aforementioned related studies, designing an efficient routing algorithm that avoids void areas remains a significant challenge. Existing approaches often struggle to balance energy efficiency, data delivery reliability, and congestion mitigation, leading to suboptimal network performance in dynamic environments. Additionally, void areas can severely affect packet transmission, leading to delays, increased energy consumption, and potential data loss. Therefore, there is a pressing need to enhance current algorithms by integrating more effective decision-making criteria and adaptive routing techniques. Addressing these challenges will improve WSN reliability and performance, extend network lifespan, and support a wider range of applications.

III. PROPOSED ROUTING ALGORITHM BASED ON TOPSIS

The proposed routing algorithm has two primary goals. First, it focuses on detecting and avoiding congestion by gathering information from neighbors about the nature of traffic around it. Second, it bypasses energy holes as soon as they form within the network topology, without expanding their area.

The proposed geographic routing algorithm to achieve these goals will be based on TOPSIS, with an enhanced criterion tailored to the problem's specification. The proposed criterion will work alongside the other critical criteria to select the best node. Additionally, the PD technique in the proposed routing algorithm can bypass energy holes without excessively relying on the border nodes of those holes. The following subsections present a full explanation of the proposed routing algorithm.

A. Developed Criteria for Congestion Prevention

The developed TOPSIS contains four critical criteria for selecting the most suitable relay node. The following are the four criteria used to determine which node is the ideal neighbor within the neighbor information table:

- **Remaining Energy:** Energy is a fundamental factor in wireless networks, as sensor nodes rely on limited battery resources, making efficient energy management critical for extending both node longevity and overall network performance. The developed routing algorithm considers the energy level a significant factor. Let the maximum battery capacity be E , the residual energy of each node is RE_i . The RE_i for each sensor is computed using the First-Order Model of [16].
- **Predicted Buffer Occupancy:** Buffer occupancy is a critical metric that indicates the extent of buffer utilization. High PBO can lead to delays in packet transmission because new packets must wait for older packets to be processed. This situation can also cause packet loss if the buffer becomes fully utilized. In this work, each node estimates the PBO of its neighbors by monitoring ongoing packet transmissions within its communication range. Initially, the PBO values in the NB-Info table are reset for all nodes. The PBO is then dynamically updated based on anticipated traffic: when a node receives a request packet, it predicts a corresponding reply that will increase the sender's buffer load, and when an event packet is detected, it estimates an increase in buffer occupancy proportional to the event packet size. The detailed procedures for resetting and updating PBO are formally described in Algorithms 1 and 2.

Algorithm 1: Reset Predicted Buffer Occupancy

Input: NB-Info table
Function ResetBufferOccupancy ()
 For all K_j in the NB-Info table Do
 $PBO_j = 0$
 EndFor
 Return Buffer occupancy reset for all nodes
End

Algorithm 2: Update Predicted Buffer Occupancy

Input: PacketMsg (Data), Sender Node K_j
Function ReceivePacketMsg (Data, K_j)
 IF Data.Type = Request Then
 $PBO_j = PBO_j + \text{Reply. Size}$
 EndIF
 IF Data.Type = event
 $PBO_j = PBO_j + \text{event. Size}$
 EndIF
End

- **Minimum Hop Count:** Data transmission in WSNs incurs high costs in terms of network resources. A low hop count is vital for minimizing power consumption and latency between the source and sink nodes. The proposed algorithm prefers selecting the neighboring node with the lowest hop count to the sink, thereby saving energy and preventing the data packet from being forwarded far from the final destination.

- **Distance:** In geographic routing, the distance between a sensor node and its neighbors remains vital and has been a cornerstone of many prior approaches. In the context of the proposed routing algorithm, prioritizing longer distances reduces latency and helps mitigate congestion by distributing traffic evenly across the network. The Euclidean Distance (ED_{ij}) between nodes N_i and N_j can be calculated using (1).

$$ED_{ij} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2} \quad (1)$$

Criteria are updated periodically in the NB-Info table for each node using two types of small control packets: Hello and Beacon messages. The Hello message is broadcast only once at the beginning to share the geographic location, distance, hop count, and residual energy. Meanwhile, Beacon periodically broadcasts to share residual energy, delivery ratio, and PBO.

On the other hand, the proposed algorithm uses PD as a procedure inside the node. PD technique aims to minimize the number of data packets sent along the same path. This helps save energy by avoiding repeated use of the same next hop on this specific path. The PD technique blocks the previous relay node once in NB-Info, avoiding excessive use of border nodes around energy holes. PD distributes the workload across all neighboring nodes and effectively bypasses energy holes without expanding them. Algorithm 3 shows the pseudocode for the developed PD technique.

Algorithm 3: The Path Deviation Technique

Input: NB-Info table
Output: The selected Next_Hop (Next Relay Neighbouring Node)
Function Select Next_Hop ()
 Candidate Node $\leftarrow \emptyset$
 For all K_j in the NB-Info table Do
 IF $PD_j = \text{True}$ Then
 Add K_j to CandidateSet
 EndIF
 EndFor
 IF Candidate set $= \emptyset$ Then
 Candidate set $\leftarrow$ NB-Info table
 EndIF
 Start TOPSIS ()
 Next_Hop $\leftarrow$ TOPSIS (Candidate)
 For all K_j in the NB-Info table Do
 IF Next_Hop_i = K_j Then
 $PD_j \leftarrow \text{False}$
 Else
 $PD_j \leftarrow \text{True}$
 EndIF
 EndFor
 Return Next_Hop
End

B. Constructing Steps for TOPSIS Matrix

The proposed algorithm uses TOPSIS to determine the preferred choice by measuring the shortest distance to the ideal (positive) position and the farthest distance from the anti-ideal (negative) position. Given the requirements, all possible best values are ideal solutions. All values that fail to meet the necessary criteria are categorized as anti-ideal solutions. These represent the least favorable options within the decision-making process. Below is a detailed breakdown of the key steps involved in the proposed TOPSIS approach.

- **Stage 1 (Establishing matrix):** n sensor nodes with m criteria are presented as a constructed matrix. Each row in the table represents a distinct alternative, while each column denotes a specific criterion for evaluation and

comparison. Equation (2) illustrates the constructed X matrix for the proposed routing algorithm based on TOPSIS. C_{ij} represented the value of j th criteria for the i th sensor node, where $(i=1,2,3,..., n)$ and $(j=1,2,3,..., m)$.

$$X_i = \begin{bmatrix} C_{11} & C_{12} & C_{13} & \cdot & \cdot & C_{1m} \\ C_{21} & C_{22} & C_{23} & \cdot & \cdot & C_{2m} \\ C_{31} & C_{32} & C_{33} & \cdot & \cdot & C_{3m} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ C_{n1} & C_{n2} & C_{n3} & \cdot & \cdot & C_{nm} \end{bmatrix} \quad (2)$$

- Stage 2 (Normalizing matrix): Normalization is a crucial step in the developed TOPSIS, ensuring that each criterion is on the same scale. Equation (3) represents the transformation normalizing the decision matrix for each element NR_{ij} .

$$NR_{ij} = \frac{c_{ij}}{\sqrt{\sum_{i=1}^n c_{ij}^2}} \quad (3)$$

A weight W_j is assigned to each criterion in the matrix, and these weights will be multiplied by the normalized array as shown in (4), where $\sum_{j=1}^n W_j = 1$.

$$V_{ij} = W_j \times NR_{ij} \quad (4)$$

- Stage 3 (Ideal and anti-ideal solution): The weighted decision matrix defines the ideal (positive) and anti-ideal (negative) solutions. Ideal criteria represent the highest possible criterion values (the more, the better), as shown in (5).

$$A^+ = \{(\max V_{ij} | i=1,2,3,...,n), j=1,2,3,...,m\} \quad (5)$$

On the other hand, an anti-ideal solution has the lowest criteria value (less is more desirable) as described in (6).

$$A^- = \{(\min V_{ij} | i=1,2,3,...,n), j=1,2,3,...,m\} \quad (6)$$

- Stage 4 (Determining distance): The next step involves the calculation of the Euclidean Distance that separates the current alternatives from the ideal and anti-ideal solutions, as shown in (7) and (8).

$$S^+ = \sqrt{\sum_{i=1}^n (V_j^+ - V_{ij})^2} \quad (7)$$

$$S^- = \sqrt{\sum_{i=1}^n (V_j^- - V_{ij})^2} \quad (8)$$

- Stage 5 (Ranking alternatives): The final step involves ranking the alternatives. In this step, all alternatives are ranked based on their similarity to the positive and negative solutions, as shown in (9).

$$K_i = \frac{S_i^-}{S_i^+} \quad (9)$$

C. Cost Analysis

In WSNs, energy is critical because sensing, communication, and data processing consume power at the sensor nodes. Among these activities, communication requires the most energy, significantly more than sensing and data processing. However, explaining the computational cost for any new proposed routing algorithm is crucial. Calculating the computational cost of the proposed routing algorithm involves a main stage: the exchange of neighbors' information states.

The number of neighbor sensor nodes, denoted by N , influences the computational complexity of the TOPSIS method, as the algorithm executes a fixed sequence of independent stages nevertheless of the input size or difficulty scale. In this context, the time complexity can be expressed as $O(N \times M)$, where N is the number of neighbors sensor nodes, and M is the number of criteria. Therefore, the entire proposed method has an $O(N \times M)$ time complexity. For simplicity, the proposed TOPSIS will not consider nodes nearest to the BS, since these critical nodes already have the BS in their NB-Info table and thus know its location. This simplification reduces computational overhead, making the overall computational cost better suited to WSN requirements.

IV. RESULTS AND DISCUSSION

The simulation results were generated using OMNeT++ 6.3 and compared with the baseline algorithms presented in [14] and [17]. Simulation experiments average the results from 100 randomly generated network topologies. The proposed routing algorithm assigned four weighting factors to the TOPSIS criteria, where $W_j \in [0, 1]$ and $\sum_{j=1}^n W_j = 1$. The developed algorithm adopts equal weights for the four enhanced criteria. A trial-and-error approach was employed, with multiple configurations systematically tested through extensive simulations. The final values were selected to achieve a balanced improvement across key performance metrics, including network lifetime, delivery ratio, and latency, thereby significantly improving the proposed algorithm's performance.

Table I provides a comprehensive list of simulation parameters, including the number of nodes, transmission range, and network size.

TABLE I. SIMULATION TERMINOLOGY AND VALUES.

Terminology	Value
Size of the field	500×500 Meter
The quantity of sensor nodes	100 Sensor Node
Sink location	(250,250)
Transmission range	120 Meter
Number of events	2,4,8, and 10 events per round
Number of rounds	200 To 2000 Rounds
Initial energy	$(15 - \text{rand}(0, 1)) \times 10^{-2}$ Joule
Radio Dissipation (E_{elec})	50nJ/bit
Transmission amplifier (E_{amp})	100pJ/bit/m ²
Sensing interval	3 Second
Beacon transmission interval	0.7 Second
Simulation duration (round)	7.5 To 28 Second
Weighting factors (α, β, γ , and δ)	0.25

The Packet Error Rate (PER) represents the ratio of transmitted packets from sensor nodes that fail to be correctly received at the intended destination, reflecting the reliability of the communication process in the network. Elevated PER due to high congestion and energy holes significantly degrades network performance and is the main issue in prior geographic routing algorithms. Fig. 2 illustrates the PER performance of the proposed Smart Geographic Routing Algorithm based on

TOPSIS (SGRT) compared with the FTR and EEGR benchmark algorithms. Fig. 2 shows that all algorithms experience a slight PER at the beginning (the first 200 rounds), varying from 8.17 to 10.15, due to the Hello message broadcast storm. However, the proposed SGRT improves the benchmark algorithm by an average of 29.3% over FTR and 16.4% over EEGR.

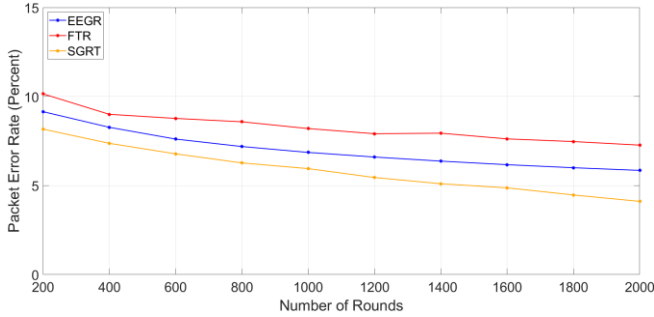


Fig. 2. Packet error rate of the proposed TOPSIS-based routing algorithm compared to the baseline algorithms.

The TOPSIS approach, combined with the four enhanced criteria and the PD technique, significantly improves PER in geographic routing. It consistently achieves a lower PER across all rounds due to the presented forwarding policy, which effectively avoids congested nodes and selects optimal forwarding paths. This approach enhances transmission reliability and ensures more stable network performance, even in dynamic WSN environments.

In addition, the PD technique improved PER levels by pushing data packets farther from energy holes through its forwarding strategy. Moreover, the proposed routing algorithm does not periodically broadcast Hello messages, unlike the FTR algorithm. Hello messages are sent only during the initialization phase. On the other hand, EEGR does not include the PBO criterion, leading to many packets being delayed during transmission. With increasing rounds and time, the proposed geographic algorithm achieved a lower PER due to more accurate decisions.

The Packet Delivery Ratio (PDR) is a key performance indicator that evaluates the effectiveness of event report transmission by measuring the successful delivery rate between sensor nodes. Fig. 3 illustrates that the proposed algorithm achieves a higher PDR than the benchmark algorithm, with an improvement of 2.6% compared with FTR and 1.16% compared with EEGR. It uses a MCDM process (TOPSIS) with tailored metrics (including PBO) that directly address the primary sources of packet errors: congestion, energy holes, and excessive control-message overhead.

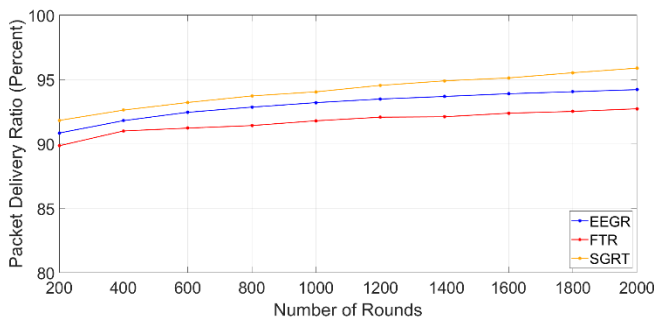


Fig. 3. Packet delivery ratio of the proposed TOPSIS-based routing algorithm compared to the baseline algorithms.

By making more informed and accurate routing decisions, SGRT ensures higher transmission reliability, enhances overall communication efficiency, and consistently achieves a significantly lower PER.

Network lifetime was dramatically improved across all experiments using the developed algorithm. Fig. 4 illustrates that the proposed routing algorithm, SGRT, achieved an average performance improvement of 28.4% over the FTR algorithm and 11.7% over the EEGR algorithm.

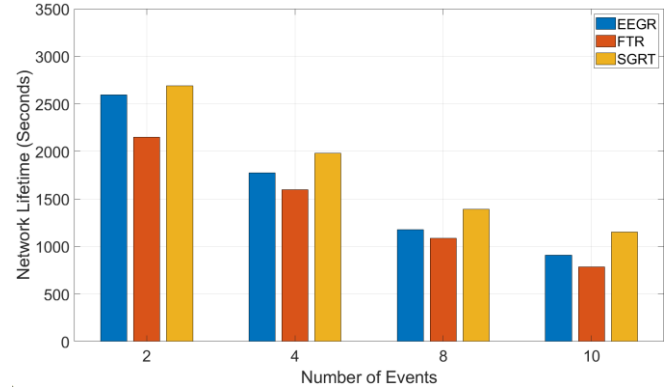


Fig. 4. Network lifetime of the proposed TOPSIS-based routing algorithm compared to the baseline algorithms.

The results indicated that the increase in network lifetime is more significant when the network is not heavily loaded, for example, when only 2 events occur per sensing round. The TOPSIS approach extends the network's total lifetime by delaying the death of its first node by avoiding paths with minimum energy levels. The minimum hop count, distance, and remaining energy criteria help balance the workload across the network by reducing reliance on congested nodes. Thus, prevents overuse and avoids the rapid energy depletion of heavily burdened nodes.

The proposed routing algorithm demonstrated strong network performance. The developed SGRT improved the latency metric over the benchmark algorithms, reducing latency by 12.2% relative to FTR and 18.2% relative to EEGR. Fig. 5 illustrates the latency for the proposed routing algorithm and the baseline algorithms. The average improvement is attributed to TOPSIS's forward policy and the limited use of control packet broadcasting. Unlike baseline algorithms, the proposed algorithm does not broadcast a Hello message whenever a sensor node changes its hop count, thereby reducing congestion.

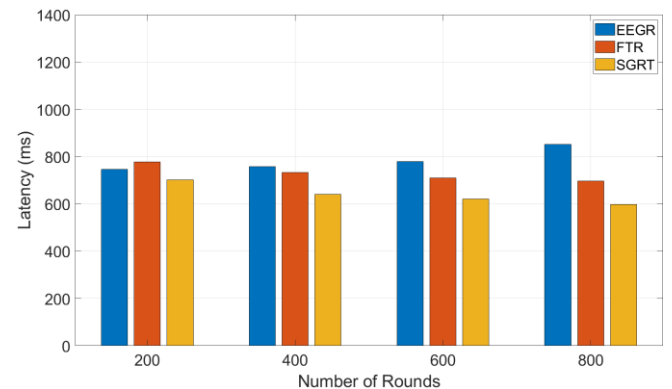


Fig. 5. Latency of the proposed TOPSIS-based routing algorithm compared to the baseline algorithm.

However, the developed routing algorithm experienced high latency, especially in the first 200 rounds (701.0021 ms), as shown in Fig. 5. This is due to the PD technique's behavior, which routes data packets along the longest paths.

V. CONCLUSION

This study presented an enhanced geographic routing algorithm for WSNs. The proposed algorithm is presented to improve network performance in terms of data transmission reliability. The proposed routing algorithm was designed based on TOPSIS. TOPSIS, an MCDM approach, enables the proposed algorithm to provide an enhanced solution that accounts for conflicting criteria. The developed routing algorithm used PBO as a critical criterion. PBO, alongside other essential criteria such as energy and minimum hop count, also accounts for congestion avoidance. The proposed routing algorithm embeds a developed PD technique that can retard the formation of energy holes and bypass them. PD prevents the continuous use of the shortest path. Thus, it prevents the same nodes from participating in the routing process, thereby preserving their energy. The proposed algorithm overcomes the drawbacks of benchmark works by avoiding congestion and preventing overuse of the same nodes during routing. Moreover, the proposed routing algorithm can easily bypass the void areas within the network topology. It also prevents these areas from expanding by avoiding repeated use of the hole's boundary nodes. An extensive simulation was conducted to validate the developed algorithm and assess its impact on performance measures relative to the benchmark algorithms. The proposed SGRT algorithm has significantly improved network performance. It improved the packet delivery ratio, reduced packet error rate and latency, and increased network lifetime.

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