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RESEARCH ARTICLE

Optimized Multi-Criteria Routing Algorithm for Durable Wireless Sensor Networks

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ABSTRACT

The Internet of Things and the Fourth Industrial Revolution (IR 4.0) rely on Wireless Sensor Networks (WSNs) as their underlying infrastructure. WSNs have recently attracted significant attention due to their crucial applications, such as monitoring applications. Geographic routing algorithms are widely used in WSNs because event location is often more critical than node identification. However, these algorithms still face challenges, such as workload imbalance and high energy consumption. Energy consumption is particularly vital in WSNs due to the sensor nodes' limited power resources. This work proposed an enhanced geographic routing algorithm based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a robust Multi-Criteria Decision-Making technique. The proposed TOPSIS-based method simultaneously incorporates four critical criteria, thereby addressing the limitations of conventional shortest-path approaches that depend solely on distance or residual energy. By integrating these carefully selected criteria, the proposed approach significantly improves network lifetime and overall performance, providing a more balanced and efficient routing strategy than previous methods. Simulation experiments were conducted to validate the proposed routing algorithm's performance compared to the EAEDR and FTR algorithms, which served as benchmarks. The results show that the developed algorithm significantly improved over the baseline algorithms regarding packet error rate, network lifetime, packet delivery ratio, and average energy consumption.

Keywords: Geographic routing, Internet of Things, Multi-criteria decision making, TOPSIS, Wireless sensor networks

Introduction

The rapid and exponential expansion of the Industry Revolution 4.0 (IR4.0) and the notion of the Internet of Things (IoT) serve as a crucial framework for future industrial innovations. [1–3] WSNs are the foundation of the IoT and smart cities. [4,5] WSNs are often characterized as multi-hop network systems consisting of a diverse range of intelligent sensor nodes. [6–8] Sensor nodes have characteristics dispersed in an auto-organizing manner and are limited by energy constraints. [9,10] Every sensor node can gather data necessary for a particular application from the surrounding environment. [11] It may also act as a data forwarder to guarantee that the data has been successfully transmitted to its intended destination. [12] The autonomous and adaptable character of WSN operations is highly sought after in several important and time-sensitive application situations, such as monitoring earthquakes, volcanic activity, and forest fires. [13,14]

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Routing in WSNs is complicated due to their significant differences from other network types, such as wired or cellular networks.[15] Geographic routing is widely utilized in WSNs as a highly effective technique, particularly because it relies on the physical location of events and nodes rather than maintaining complex routing tables. Geographic algorithms have many advantages, such as low end-to-end latency, scalability, flexibility, and high delivery rates. However, geographic routing approaches still have many open issues, such as significant overhead, void areas problems, and an imbalanced workload, reducing the network's lifespan.[16]

Sensor nodes are supplied by small and compact batteries. Occasionally, it may be impossible to replace or recharge such batteries. Thus, energy efficiency is a significant focus of WSN.[17–19] One of the most serious issues with traditional geographic routing algorithms and their modifications is that they rely on a single factor, which is often distance, throughout the routing process. Consequently, they cannot effectively address various challenges, such as high congestion and excessive energy consumption. Even if two or multiple criteria are applied to the routing process, the forwarding strategy is limited to adhering to the rules set by these criteria.

Existing geographic routing algorithms have utilized many factors, such as the distance to the destination, the remaining energy of nodes, and the link quality between neighboring nodes. Consequently, Multi-Criteria Decision-Making (MCDM) algorithms have been introduced to incorporate more criteria for improving network longevity.[20,21] Many types of MCDM approaches have been proposed, such as the Analytic Hierarchy Process (AHP), Elimination and Choice Expressing Reality (ELECTRE), and Weighted-Sum Models (WSMs).[22,23] WSMs are creative solutions used widely in WSN routing, determining the relative importance of each criterion.[24] In addition, they involve aggregating different criteria to arrive at a single decision metric.[25] However, these approaches suffer from many drawbacks, such as selecting appropriate weights that must be subjective. Also, the WSMs methods might not identify all optimal solutions. Moreover, they cannot adaptively change their forwarding policy and respond to different network conditions. The limitations of existing geographic routing algorithms motivate this work to propose a new routing algorithm for WSNs. Optimized Multi-Criteria Routing Algorithm (MCRA) utilizes a multi-criteria decision-making method called Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This approach introduces enhanced criteria to select the most suitable neighbor for data forwarding toward the Base Station (BS).

The remainder of this article is structured as follows. The next section reviews state-of-the-art research and highlights the motivation for geographic routing algorithms in WSNs. After that, a detailed description of the proposed routing algorithm is provided, followed by the introduction of the enhanced criteria for the enhanced TOPSIS method The subsequent section presents the network model adopted in this study, together with a cost analysis of the proposed algorithm. This is followed by a description of the simulation setup and a comprehensive discussion of the obtained results. Finally, the article concludes with a summary of the main contributions and findings.

Related works

Previous approaches have presented many solutions to efficiently deal with the workload imbalance and high energy consumption in geographic routing algorithms in WSNs. The related works have been extensively analyzed to position the proposed algorithm regarding these problems.

Gangal et al.[26] proposed a hierarchical and distributed geographic routing approach that combines the LEACH protocol with the AHP. Nodes maintain a matrix of threshold values, calculated using AHP based on energy and distance to the sink, to determine their probability of becoming cluster heads autonomously. However, this work depends on AHP, which requires complex pairwise comparisons, which makes it computationally expensive and not suitable for real-time decision-making in WSNs. Moreover, the work used only two criteria for routing decision-making, which are the energy and the distance. Considering only two criteria made the developed algorithm unable to change its forwarding policy adaptively, and it cannot respond to different network conditions.

Pandey & Singh[27] introduced a new clustering method that employs the TOPSIS algorithm to select cluster heads. The authors claimed that the proposed model balances the load and optimizes the energy effectively using five parameters. The five criteria are remaining energy, distance to the BS, density, average distance of nodes within the range, and the standard deviation of the distance of nodes within the range. However, the entire work was based mainly on one solo consideration of the distance, neglecting other critical criteria such as reliability and hop count. Moreover, increasing the number of criteria for the presented TOPSIS will have a dramatic effect on the time and the cost complexity for the proposed work.

Biswas & Samanta[28] presented a novel geographic routing algorithm for WSNs based on a multiweighted sum method. The entitled algorithm, Fault-Tolerant Routing (FTR), utilizes hop count to select the most suitable node from neighbors to relay reports toward the final destination. The proposed algorithm incorporates several criteria, including residual energy, delivery ratio, and hop count. However, the primary criterion is the minimum hop count, which leads to constraints on the workload of specific nodes rather than others.

Hang et al.[29] presented an Energy Aware Event Driven Routing (EAEDR) Protocol to enhance the traditional geographic routing algorithms. In the proposed algorithm, one or two of the best nodes are chosen to forward packets based on the event type. The next-hop selection criteria for the proposed routing algorithm are remaining energy, distance to sink, and distance to source. However, considering the high-priority event, the multipath presented significant overhead in managing the routing table.

Sen et al.[30] presented a Triangular Fuzzy Numbers (TFNs) with the TOPSIS method to choose the CHs in WSNs. The number of cluster heads is optimized by considering six parameters: reliability, residual energy, the number of neighbor nodes, the distance from the sink (BS), the average distance of non-cluster nodes, and the distance ratio. However, the work segregated the entire network into only 14 clusters. In addition, the included criteria focus basically on the distance to the BS and neglect the distance between the neighboring nodes.

Jian et al.[31] presented a High-Reliability Low Latency Intelligent Geographic routing (HRLLIGR) algorithm based on an enhanced Greedy Perimeter Stateless Routing (GPSR) algorithm. The entire work is based on the mobile nodes in dynamic topology. The proposed work enhanced link reliability through greedy forwarding, guided by link stability metrics. Additionally, latency caused by void areas is minimized using area prediction-based forwarding. However, the algorithm based on the mobile nodes faced a significant challenge. The primary limitation of this research lies in the complexity of communication between mobile nodes and the BS, which arises from the dynamic and continuously changing network topology.

By taking all limitations of the mentioned related studies, designing an efficient geographic routing algorithm is a challenging task. The analysis of the related works revealed that many geographic routing algorithms rely on one or more criteria such as residual energy, distance, and link quality to select the most suitable relay node. However, these algorithms generally lack the ability to adapt their forwarding strategy to dynamic network conditions, as they cannot adjust the forwarding policy based on the interrelationships among the criteria. To overcome these limitations, several MCDM-based approaches have been proposed for geographic routing. Nevertheless, most of these methods have demonstrated inadequate performance, particularly in scenarios with congested nodes, which often result in high energy consumption.

The main steps of the proposed routing algorithm based TOPSIS

The TOPSIS approach is a multi-criteria technique presented for the first time by C.L. Hwang and K. Yoon in 1981 to choose the best option from a group of choices.[32] Fundamentally, TOPSIS helps decision-makers determine which option is best by comparing each one to the best option based on several criteria. TOPSIS was used widely to design routing algorithms in WSNs, and it was a preferable choice over other methods for many reasons. Some of these reasons are that TOPSIS is straightforward to implement, scalable, and flexible in criteria weighting. Moreover, TOSIS can be integrated with other techniques, such as fuzzy.[33] Lastly, TOPSIS can effectively deal with many complex and incompatible criteria.

The proposed routing algorithm utilizes TOPSIS to determine which choice is preferable. It uses the closest distance to the ideal (positive) position and the furthest distance from the anti-ideal (negative) position. All feasible best values are ideal (positive) solutions given the requirements. On the other hand, all of the worst values that do not meet the criteria are included in the anti-ideal (negative) solutions. The following are the detailed main steps for the proposed TOPSIS method.

Stage 1: Establishing the matrix

For each sensor node, the *SN* sensor node with *m* criteria is presented as a constructed matrix where each row represents an alternative, and each column represents a criterion. Eq. (1) illustrates the constructed X_i matrix for the proposed routing algorithm based on TOPSIS. C_{ij} represented the value of *jth* criteria for the *ith* sensor node where (i= 1,2,3, …,n) and (j=1,2,3,…, m).

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

Stage 2: Normalizing the matrix

Normalization is a crucial step in the proposed algorithm based on the TOPSIS because it ensures that each criterion is on the same scale and contributes equally to the decision-making process. Eq. (2) represents the transformation that is used to normalize the decision matrix for each element NR_{ij}.

$$NR_{ij} = C_{ij} / \sqrt{\sum_{i=1}^{n} C_{ij}^2} \tag{2}$$

A weight W_j is assigned to each criterion in the matrix; the weights are then multiplied by the normalized matrix using Eq. (3).

$$V_{ij} = W_j * NR_{ij} \text{ where } \sum_{j=1}^{n} W_j = 1 \tag{3}$$

Stage 3: Finding the ideal and anti-ideal solution

The weighted decision matrix defines the ideal (positive) and anti-ideal (negative) solutions. Ideal or positive criteria represent the highest criteria values (the higher, the better), as shown in Eq. (4).

$$A^+ = \left(V_1^+,\ V_2^+,\ V_3^+, \ldots,\ V_n^+\right)$$

$$A^+ = \left\{(max\ V_{ij} | i = 1, 2, 3, \ldots .m),\ \ j = 1, 2, 3, \ldots .n\right\} \tag{4}$$

In contrast, the anti-ideal (negative) solution has the lowest criteria value (less is more desirable), as shown in Eq. (5).

$$A^- = \left(V_1^-,\ V_2^-,\ V_3^-, \ldots,\ V_n^-\right)$$

$$A^- = \left\{(min\ V_{ij} | i = 1, 2, 3, \ldots .m),\ \ j = 1, 2, 3, \ldots .n\right\} \tag{5}$$

Stage 4: Determining the distance

The next step within the proposed algorithm involves the calculation of the distance that separates the current alternatives from the ideal and anti-ideal solutions, as shown in Eqs. (6) and (7).

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_j^+ - v_{ij}\right)^2} \tag{6}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_j^- - v_{ij}\right)^2} \tag{7}$$

Stage 5: Ranking the alternatives

The final step in the proposed algorithm represents the ranking of the alternatives. In this step, all alternatives are ranked based on their closeness to the ideal solution and distance from the anti-ideal solution using Eq. (8).

$$K_i = S_i^- / S_i^+ + S_i^- \text{ where } 0 \le K_i \le 1 \tag{8}$$

The following section will detail the proposed criteria used within the proposed routing algorithm to build the proposed TOPSIS matrix.

The proposed criteria for TOPSIS

The proposed algorithm ensures optimum routing by choosing the most suitable neighbor node within the transmission range as the packet is transferred from the source node to BS via the best path. Using TOPSIS, the best node in the neighbor's information table is chosen for each sensing round, considering energy consumption as a primary target. The following are the four proposed criteria used to determine the most suitable node from the neighbor nodes:

Euclidean Distance (ED): The distance between any sensor node and its neighboring nodes is a crucial criterion and fundamental in geographic routing. This parameter guarantees that event reports are forwarded efficiently to the destination. The main idea is to forward data packets to the farthest neighboring node, which will also be the closest node to the BS among the neighboring nodes.[28] The proposed routing approach ensures that each hop moves the data packet significantly closer to the BS, optimizing the routing path and improving the network's efficiency. Eq. (9) is used to calculate ED between any two neighboring nodes.

$$ED_{(N_i, N_j)} = \sqrt{(X_j - X_i)^2 + \ (Y_j - Y_i)^2} \tag{9}$$

where the coordinates of nodes N_i and N_j are represented by (X_i, Y_i) and (X_j, Y_j), respectively.

Remaining Energy (RE): Energy efficiency is critical due to sensor nodes' limited battery life. The proposed routing algorithm considers enhancing the network lifetime as a primary goal. Any sensor node N_i will inform all its neighbors N_j about its RE_i value. This behavior ensures that the best route is selected between a node and its immediate neighbor and across the entire path to the BS. Thus, this parameter is critical in the proposed algorithm to prevent routing through dying nodes or weak paths with low energy levels. The proposed TOPSIS algorithm considers the higher energy value as a preferable choice.

Link Reliability (LR): Alerting BS about an event is the main priority in event-driven WSNs. Therefore, link reliability is a crucial need and ensures reliable packet transmission. LR_{ij} between any two nodes (N_i and N_j) indicates link trustworthiness.[28] It is calculated as the ratio of packets received by N_i to packets sent by N_j. Packet loss is more likely on links with a lower *LR*. A link with a higher *LR* is preferable to ensure the link quality. Eq. (10) calculates the *LR* of any nearby node N_i on node N_j.

$$LR_{ij} = N_iRN_j/BN_j \tag{10}$$

Where N_iRN_j is the number of beacon packets that N_i received from node N_j and BN_j is the number of beacon packets broadcast by N_j.

The proposed performance analysis tool calculates the *LR* periodically by exchanging the Beacon messages and tracking the number of packets the neighbors receive. The Beacon message has a field, namely the *Bcon_ID*. *Bcon_ID* is a unique identifier of the Beacon message, starting with one and incremented by one at each beacon broadcasting interval. Each node also has a column *Bcon_count* within the Neighbor Information (NB-Info) table initialized table started as 0. Upon receiving a beacon from neighbor N_j, N_i stores *Bcon_ID* and increments the Beacon counter by 1. Therefore, dividing *Bcon_count* by *Bcon_ID* will be the delivery ratio between N_i and N_j. With increasing time, nodes broadcast and receive more beacons, making *LR* increasingly accurate.

Minimum Hop Count (MHC): Data transmission in WSNs incurs significant costs in terms of both energy and time. *MHC* is essential to minimize energy consumption and end-to-end delay from the source node to the BS. *MHC* criterion helps prevent redundant path deviations and ensures that the routing process is more direct by avoiding superfluous detours. The proposed algorithm prefers to select the neighboring node with the low *MHC* to the BS, thereby saving energy and preventing the data packet from being forwarded far from the final destination.

All four criteria were calculated easily, without the need for additional equipment or high complexity, through the exchange of neighbor information. The neighbors' information is exchanged periodically using Hello and Beacon messages (control packets) and stored inside the NB-Info table for each sensor node. Both routing control packets are small in size to conserve energy and prevent network congestion. Hello messages are broadcast only once at the beginning to share the hop count, geographic location, and the residual energy for each node, as shown in Fig. 1, which represents the fields or the contents of the Hello packet. Fig. 2 represents the contents of the Beacon packet containing Beacon ID, remaining energy, and hop count. All these parameters are essential to support the updating process of the enhanced criteria before storing them in the NB-Info table. Fig. 3 illustrates an example of the updating process of the proposed criteria values within the NB-Info table for sensor node S10.

Table 1. TOPSIS matrix for SN_{44}.

Sensor Node ID	ED	RE	LR	MHC
62	62.12	13.20	1.00	2
47	39.53	13.25	1.00	2
49	32.43	13.82	1.00	2
89	39.09	13.20	0.92	3

Table 2. The normalization matrix for SN_{44}.

Sensor Node ID	ED	RE	LR	MHC
62	0.18	0.14	0.15	0.39
47	0.13	0.14	0.15	0.39
49	0.12	0.15	0.15	0.39
89	0.13	0.14	0.14	0.58

Fig. 4 illustrates an example taken from the developed simulation regarding the TOPSIS steps for the sensor node SN_{44} at the left of the network topology.

The mentioned sensor node (SN_{44}) constructed the TOPSIS matrix for four neighbor nodes and four mentioned criteria, as shown in Table 1, where each row indicates an alternative and each column denotes a criterion. While Table 2 represents the normalized matrix for the same sensor node SN_{44}.

The ideal and anti-ideal solutions, which represent the third stage of the proposed TOPSIS, are shown in Eqs. (11) and (12) for the mentioned sensor node SN_{44}.

$$A^+ = (0.18,\ 0.15,\ 0.15,\ 0.39) \tag{11}$$

$$A^- = (0.12,\ 0.14,\ 0.14,\ 0.58) \tag{12}$$

Eqs. (13) and (14) illustrate the fourth stage of the developed TOPSIS.

$$S_{44}^+ = (0.0039,\ 0.2104,\ 0.2142,\ 0.2036) \tag{13}$$

$$S_{44}^- = (0.254,\ 0.1846,\ 0.1922,\ 0.2125) \tag{14}$$

The alternative options values based on the proposed routing algorithm from the last stage (SN_{62}=

Node ID	Beacon ID	Remaining Energy	Hop Count

Fig. 1. The content of the Hello message.

Node ID	Pos_x	Pos_y	Remaining Energy	Hop Count

Fig. 2. The content of the Beacon message.

0.91, SN_{86}= 0.52, SN_{47}= 0.49, SN_{49}= 0.38) show that sensor node SN_{62} will act as a forwarder node for sensor node SN_{44} for this sensing round.

Network model

In the proposed network model, K is the number of sensor nodes, K_i (i = 0,1,2, 3,..., i-1), that are randomly scattered in a Two-Dimensional *2D* geographical area with dimensions of (*X*, *Y*). Any two nodes, such as K_i and K_j, can communicate directly if the Euclidean Distance ED_{ij} between them is less than or equal to their transmission range *D*. The proposed routing algorithm uses a multi-hop communication style to forward data packets towards the BS, as shown in Fig. 3. Any node not a neighbor of the BS will choose one of its neighbors as the forwarding node to transmit its sensed data to the BS according to the NB-Info table. The NB-Info table is periodically updated by exchanging the routing control packets, providing all the necessary information for the sensor node to construct its TOPSIS matrix.

Early on, every sensor node sets its hop count and next hop as $HC_i = \infty$ and next hop = 0 while BS broadcasts Hello with a hop count and next hop as 0. Whenever any node receives a hello message from a neighbor. K_i will compute the distance and store the energy level inside the NB-Info table. If HC_i which was initially set as ∞ is greater than $HC_j + 1$. K_i assign its hop count as $HC_j + 1$ and resend a Hello message to inform others. On the other hand, Beacon messages are broadcast periodically to update the neighbor's information inside K_i in a similar manner. Algorithm 1 outlines the pseudocode steps for the Hello and Beacon message exchanges and generating NB-Ino table.

Cost analysis

In WSNs, energy is critical as sensing, communication, and data processing activities consume power

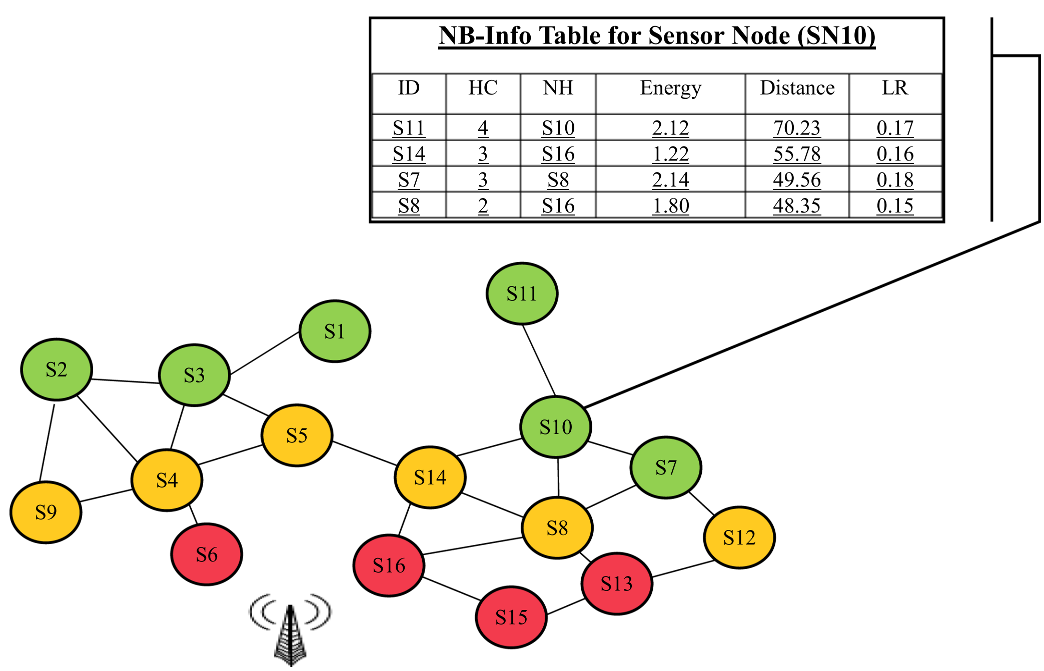

Fig. 3. Updating the proposed criteria values.

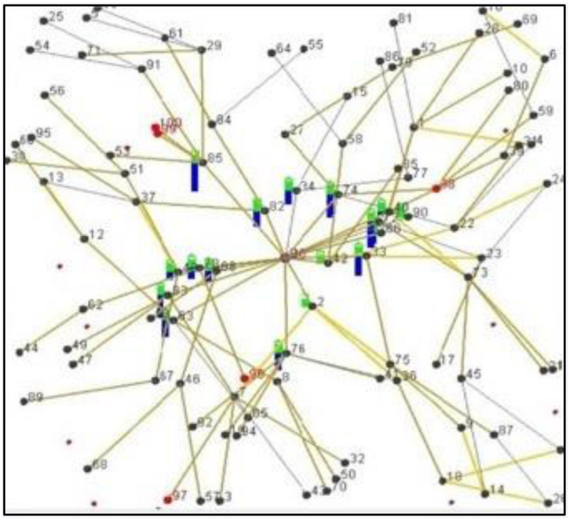

Fig. 4. A Simulation scenario for the proposed routing algorithm.

in the sensor nodes. Among these activities, communication requires the most energy, significantly more than sensing and data processing. Therefore, explaining the computational cost for any new proposed routing algorithm is important. Calculating the computational cost of the proposed routing algorithm involves a main stage, which is the exchange of the neighbor's information state. The number of neighbor nodes N affects the computational complexity of the TOPSIS method because TOPSIS executes a fixed number of independent stages regardless of input size or problem complexity. In this context, its time complexity can be expressed as O(N, M), where N is the number of neighbors, and M is the number of criteria. Therefore, the proposed method has an O(N, M) total time complexity. For simplicity, the proposed TOPSIS will not consider the nearest nodes to the BS since these critical nodes already have the BS included in their NB_Info Table and thus know the location of the BS. This simplification reduces computational overhead, making the total computational cost suitable for the requirements of WSNs.

Simulation setup

This section presents a precise analysis of the simulation configurations that will be illustrated in detail for the proposed geographic routing algorithm based on TOPSIS. This section presents a precise analysis of the simulation configurations that will be illustrated in detail for the proposed geographic routing algorithm based on TOPSIS. The developed DES simulator based on the JAVA programming language was used to evaluate the proposed algorithm and compare it with benchmark work results reimplemented in the

Algorithm 1: Control packet exchange for generating NB-Info table.

Input: Hello message, Beacon message
Output: NB_Info Table

Function Initialization ()
  If K_i is BS Then
    Broadcast (Hello Message);
  End If
End Function
Function Received Hello ()
  If K_i receives Hello from a neighbor K_i
    Compute $ED_{(k_i,k_j)}$using Eq. (9)
    Store *Node_ID*, *Pos-x*, *Pos-y*, *HC*, and $ED_{(k_i,k_j)}$ in NB-Info table;
  End If
End Function
Function Send Hello ()
  After receiving a Hello message from any node K_j
  For each K_j in the NB-Info table Do
    Broadcast (Hello);
  End For
End Function
Function Send Beacon ()
  For each K_j in the NB-Info table Do
    Send $ED_{(k_i,k_j)}$, HC_i, and *Energy*, and to all Neighbours
  End For
End Function
Function Received Beacon ()
  If K_i receives Hello from a neighbor K_i
    Store All the needed Information in the NB-Info table
    Compute the criteria To Build the TOPSIS matrix
    Update all criteria inside the NB-Info table;
  End IF
End Function

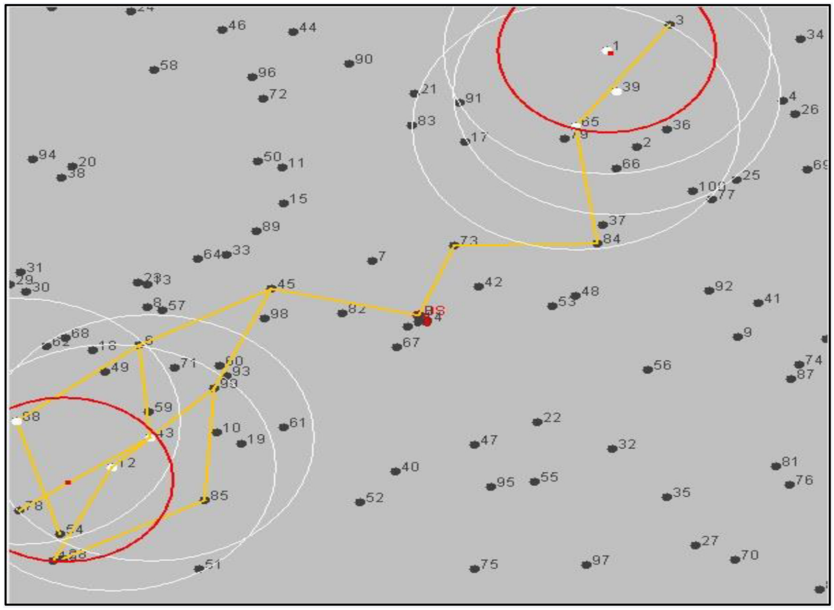

Fig. 5. Simulator interface.

developed simulator. The WSN simulation tool is used specifically for routing process testing. This work has chosen the EAEDR and the FTR algorithms as baseline algorithms.[28,29] These algorithms were chosen as baselines because they represent state-of-the-art approaches for energy efficiency and high delivery ratio. This allows for a fair evaluation of the proposed algorithm in terms of both energy optimization and reliability, which are the two main challenges in WSN routing.

The simulation setup follows the benchmark methodology commonly adopted in prior works (FTR and EAEDR)[28,29] to ensure fair comparison. This work conducted simulations of over 100 random different topologies with varying events per round (2, 4, 8, and 10). The number of simulation rounds varied from 100 to 2000 to capture both short-term and long-term network behavior, with 100 different runs for the event locations, repeated 100 times for statistical confidence. A total of 100 sensor nodes were randomly and uniformly deployed in a (600×600) area, with the BS positioned at the center (300,300), as shown in Fig. 5. This topology was deliberately selected because random uniform deployment with a centrally located BS is used in the benchmark's scenario in event-driven WSN studies. It provides a neutral and unbiased environment that avoids favoring any particular routing strategy, thereby ensuring fair and consistent comparison with benchmark algorithms.

The transmission range of all nodes is 120 meters, and all sensor nodes have the same initial amount of energy. To accurately compare our proposed method with the baseline algorithms, the proposed performance analysis tool takes the average simulation results of 100 different random network topologies. In the proposed routing algorithm, four distinct weighting factors are assigned to the TOPSIS criteria, where $W_j \in [0, 1]$ and $\sum_{j=1}^{n} W_j = 1$. Unlike the benchmark algorithm, which equally assigns 0.3 to all criteria, the proposed algorithm in this work adopts differentiated weights: distance ($\alpha = 0.3$), remaining energy ($\beta = 0.3$), link reliability ($\Delta = 0.3$), and minimum hop count ($\Omega = 0.1$). This distribution emphasizes the higher importance of distance, energy, and reliability over the hop count criterion in event-driven WSNs. Due to the absence of a universally accepted analytical method for determining weights, a trial-and-error process was employed, in which multiple configurations were systematically tested through extensive simulations. The final values were selected for their ability to achieve a balanced improvement across key performance metrics, including network lifetime, energy efficiency, delivery ratio, and latency, thereby significantly contributing to the enhanced performance of the proposed algorithm.

In this study, residual energy and energy consumption was computed using the First-Order Radio energy model,[34] which is widely adopted in WSN simulations. Detailed simulation parameters are comprehensively listed in Table 3.

Results and discussion

Packet Error Rate (PER), network lifetime, latency, Average Energy Consumption (AEC), and Packet Delivery Ratio (PDR) are the main metrics that indicate

Table 3. Simulation terminology and values.

Terminology	Explanation	Value
Field Size	Height and the width of field size in meter	(600×600)
Number of Sensor Nodes	Total number of deployed sensors	100
BS	Location of the BS within network topology	(300,300)
Transmission Range	Transmission range for each sensor node	120
Number of Events	Number of events per round	2,4,8,10
Number of Rounds	Number of sensing rounds	200 to 2000
Initial Energy	Initial energy for each sensor node in the joule	$(15 - \text{rand}\ (0, 1)) \times 10^{-2}$
Radio Dissipation (E_{elec})	Energy consumed to run the transmitter or receiver	50nJ/bit
Transmission amplifier (E_{amp})	Energy consumed by the transmit amplifier	100pJ/bit/m^2
Residual Energy	Residual energy for each sensor node	
Energy Threshold	Threshold which determines the dying nodes	0.1 Joule
Weighting Factors	α, β, δ, and Ω	0.3, 0.3, 0.3, 0.1

the network's efficiency and reliability within the WSN environments. The following are the experimental results for the proposed algorithm compared with the baseline algorithms (FTR and EAEDR) regarding these metrics.

PER

PER is a critical metric in WSN, representing the ratio of lost packets to the total number of packets sent and reflecting the reliability of data transmission. Fig. 6 compares the proposed algorithm with the EAEDR and FTR algorithms, demonstrating consistently lower PER values for the proposed method across all rounds. This improvement highlights its enhanced reliability in data delivery. The proposed algorithm exhibits stability and resilience over time, with PER decreasing as the rounds progress, largely due to the LR criterion, which becomes more accurate over time.

Furthermore, the energy and hop count criteria help balance network usage by preventing the overloading of specific nodes, thereby reducing retransmissions and ensuring smoother data delivery to the BS. Overall, it achieves a total average reduction in PER of 29.2% compared to the FTR algorithm and 3.4% compared to the EAEDR algorithm, demonstrating superior performance.

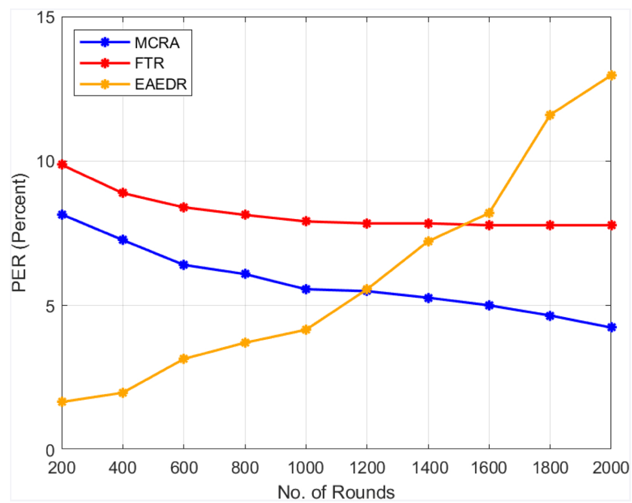

Fig. 6. PER for different numbers of rounds.

Network lifetime

Network lifetime, a critical performance metric in WSNs, is defined as the duration from network initialization until the first node depletes its energy. It reflects the network's sustainability and efficiency, making it a primary focus of WSN research. Fig. 7 illustrates the superior performance of the proposed routing algorithm in extending network lifetime compared to the benchmark algorithms. This improvement, averaging 19.6% over the FTR algorithm and 8.3% over the EAEDR algorithm, is primarily attributed to the TOPSIS-based approach, which effectively avoids routing through low-energy paths.

Moreover, the extended network lifetime indicates a more balanced energy consumption among sensor nodes, demonstrating that the proposed algorithm distributes workload effectively and prevents early depletion of specific nodes, which is the main issue in the benchmark algorithms.

Latency

Latency refers to the average time required for an event report to travel from a source node to the base station. In WSNs, low latency is essential for applications that require timely data delivery, such as real-time monitoring and emergency response systems. Eq. (15) calculates the latency for the proposed algorithm and the baseline work.

$$Latency = \sum_{i=1}^{N} (RT_i - ST_i)/N \tag{15}$$

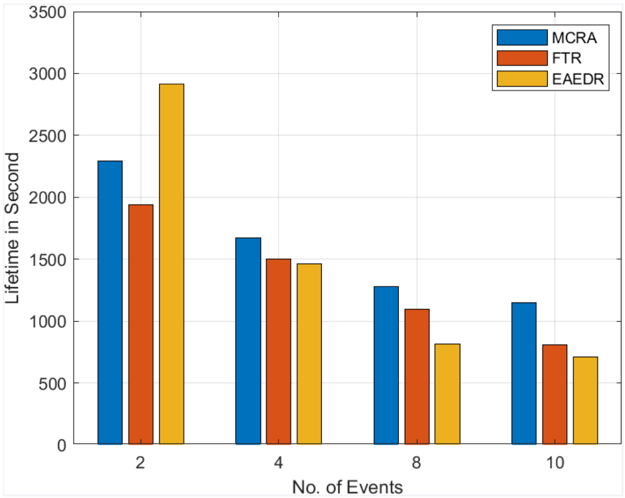

Fig. 7. Lifetime for different numbers of events.

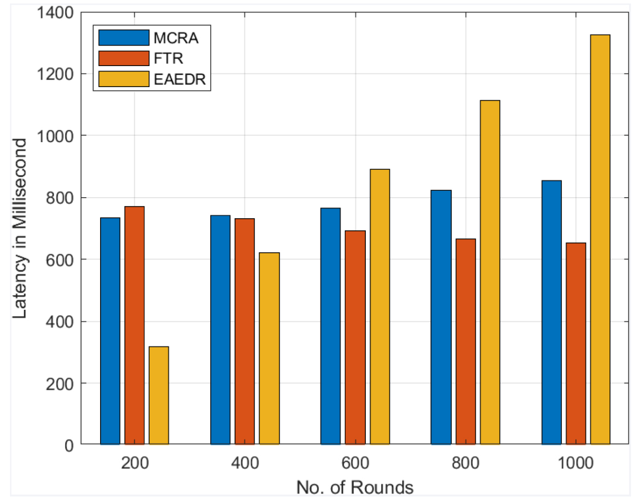

Fig. 8. Latency with different numbers of rounds.

Where N is the total number of reports delivered by the BS. While RT_i and ST_i are received and send time for *ith* event reports, respectively. Fig. 8 compares the latency of the proposed routing algorithm with the baseline algorithms, showing that both the proposed algorithm and the FTR algorithm initially experienced relatively high latency (approximately 750 ms). This is primarily due to the frequent exchange of control packets, such as Hello messages, and the delay introduced by the majority voting process used to confirm an event before transmitting it to the BS. During the first 200 rounds, the proposed algorithm achieves slightly lower latency (4% improvement) compared to FTR. This improvement is attributed to the TOPSIS-based routing method, which avoids weak nodes by considering the energy levels of neighboring nodes, thereby enhancing data transmission efficiency.

However, as the rounds progress and some nodes deplete their energy, the latency in the proposed algorithm gradually increases. This is because the algorithm deliberately avoids critical, energy-depleted nodes, often requiring data packets to traverse longer paths. Although this strategy balances energy consumption and prevents overloading key nodes, it increases latency over time. In contrast, the FTR algorithm, which does not optimize workload distribution, maintains lower latency in later rounds. As a result, the FTR algorithm outperforms the proposed algorithm by 11.9% across all simulation experiments. On the other hand, the EAEDR algorithm initially exhibits very low latency; however, its latency increases dramatically as the number of rounds increases. Overall, the proposed algorithm enhances latency performance by an average of 8.2% compared to the EAEDR algorithm.

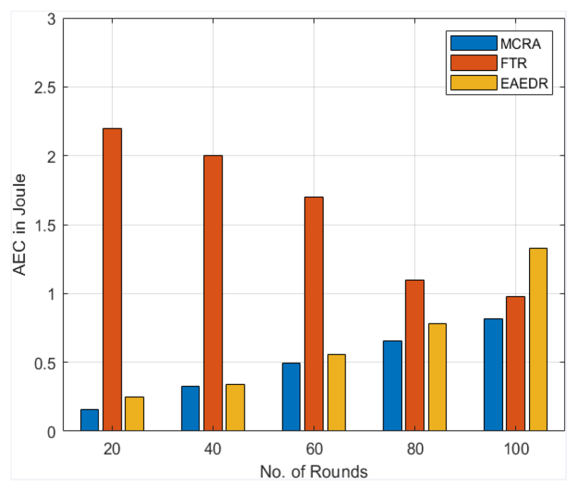

Fig. 9. AEC with different numbers of rounds.

AEC

The developed simulator can measure additional performance metrics, such as the AEC, which was not previously presented in the benchmark works. Eq. (16) calculates the AEC for the proposed and baseline algorithms.

$$AEC = \sum_{i=1}^{nodes} \left(initial\ energy_i - RE_i\right) /No.\ nodes \tag{16}$$

Fig. 9 shows the AEC that compares the energy consumed per different number of rounds under two events per round. Fig. 8 shows how energy consumption within the presented algorithms increases with increasing rounds. AEC remains relatively low for two events per round and increases gradually over time. This indicates that the proposed algorithm ef-

Table 4. ANOVA (p-values) for the evaluated performance metrics across the three algorithms.

Performance Metric	EAEDR Vs. MCRA	FTR Vs. MCRA	Significance ($p < 0.05$)
PER	0.004	0.0008	Significant
Network Lifetime	0.0012	0.0003	Significant
Latency	0.021	0.014	Significant
AEC	0.008	0.0005	Significant
PDR	0.013	0.009	Significant

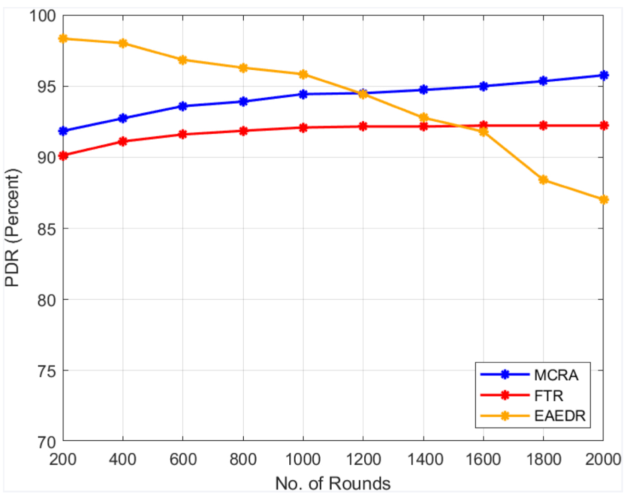

Fig. 10. PDR with different numbers of rounds.

fectively has low energy consumption under low-load conditions by selecting energy-efficient paths and balancing routing load distribution. The simulation results prove that the proposed algorithm is particularly effective in low to moderate-load environments. It can sustain energy-efficient routes in these scenarios by avoiding unnecessary energy depletion. This characteristic makes the algorithm well-suited for WSN applications, such as fire detection or border monitoring, where events are intermittent rather than constant.

PDR

PDR is an important metric used in networking to measure the success rate of data packets being successfully delivered from the sender to the receiver. The PDR can be calculated using Eq. (17).

$$PDR = \frac{No.\ of\ Received\ Event\ Reports}{No.\ of\ Sent\ Event\ Reports} * 100\% \quad (17)$$

Fig. 10 illustrates the PDR for the proposed and benchmark routing algorithms. The proposed routing algorithm provides higher PDR than the benchmark algorithms. The proposed routing algorithm achieved a total average of 94% regarding PDR, which presents a WSN with high performance and quality.

To validate the robustness of the results, a one-way Analysis of Variance (ANOVA) was conducted on the obtained data. Table 4 presents the ANOVA p-values for the evaluated performance metrics across the three algorithms. The results confirm that the observed improvements are statistically significant at the 95% confidence level ($p < 0.05$).

Conclusion

This research proposed an enhanced geographic routing algorithm based on the TOPSIS method to extend the network lifetime in WSNs. The proposed algorithm is presented to overcome open issues within the current geographic routing algorithms based on TOPSIS. In contrast to earlier TOPSIS-based methods that primarily rely on energy and distance as selection criteria, the proposed algorithm advances beyond these limitations. It determines the most suitable relay nodes by incorporating four refined criteria while explicitly considering the underlying network topology. Integrating critical criteria allows the algorithm to distribute the workload, prevent critical nodes from being overburdened, and enhance overall network performance.

Additionally, the algorithm ensures energy efficiency by utilizing the remaining energy value and considering the energy levels across the entire path. The algorithm prioritizes network lifetime and energy efficiency. However, it comes with a trade-off in latency. The approach does not explicitly optimize the time required for data packet delivery. The proposed algorithm demonstrates significant improvements over the baseline FTR algorithm, achieving an average enhancement of 15.4% in PER, 14.9% in network lifetime, and 1.46% in PDR. Future work will aim to extend and test the proposed method to large-scale WSNs, evaluating performance and scalability under more extensive network deployments.

Authors' declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any

Figures and images that are not ours have been included with the necessary permission for re-publication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Basrah.

Authors' contributions statement

Supervision and simulation validation: G.H.A. and M.S.A.; visualization and writing—original draft: G.H.A and H.A.A; review and editing: G.H.A, M.S.A., and T.N.A. All authors have read and agreed to the published version of the manuscript.

Data availability

The data supporting this study's findings and the simulation tool are available from the corresponding author upon reasonable request or by citing this publication.

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خوارزمية التوجيه متعددة المعايير المُحسَّنة لشبكات الاستشعار اللاسلكية طويلة العمر

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الخلاصة

يعتمد إنترنت الأشياء (IoT) والثورة الصناعية الرابعة (IR 4.0) على شبكات الاستشعار اللاسلكية (WSNs) كبنية تحتية أساسية لها. وقد جذبت شبكات الاستشعار اللاسلكية (WSNs) مؤخرًا اهتمامًا كبيرًا نظرًا لتطبيقاتها الحيوية، مثل تطبيقات المراقبة. تُستخدم خوارزميات التوجيه الجغرافي على نطاق واسع في شبكات الاستشعار اللاسلكية لأن موقع الحدث غالبًا ما يكون أكثر أهمية من تحديد ماهية عقدة الاستشعار. ومع ذلك، لا تزال هذه الخوارزميات تواجه تحديات، مثل عدم توازن عبء العمل والاستهلاك العالي للطاقة. يُعد استهلاك الطاقة أمرًا حيويًا بشكل خاص في شبكات الاستشعار اللاسلكية نظرًا لموارد الطاقة المحدودة لعقد الاستشعار. اقترح هذا العمل خوارزمية توجيه جغرافية مُحسّنة تستند إلى تقنية ترتيب الأفضلية حسب التشابه مع الحل المثالي(TOPSIS)، وهي تقنية قوية لاتخاذ القرارات متعددة المعايير. تأخذ الطريقة المقترحة، المستندة إلى TOPSIS، في الاعتبار أربعة معايير حاسمة بشكل متزامن، بما يسهم في تجاوز القيود المرتبطة بأساليب أقصر مسار التقليدية التي ترتكز حصرا على المسافة أو الطاقة المتبقية. من خلال دمج هذه المعايير المختارة بعناية، يُحسّن النهج المقترح بشكل ملحوظ عمر الشبكة وأدائها العام، مما يوفر استراتيجية توجيه أكثر توازناً وفعالية من الطرق السابقة. تم إجراء تجارب محاكاة لتقييم أداء خوارزمية التوجيه المقترحة مقارنةً بخوارزميتي EAEDR وFTR اللتين استُخدمتا كمعايير مرجعية. وتُظهر النتائج أن الخوارزمية المطَورة حققت تحسناً ملحوظاً على الخوارزميات الأساسية من حيث معدل خطأ الحزم، وعُمر الشبكة، ونسبة تسليم الحزم، ومتوسط استهلاك الطاقة.

الكلمات المفتاحية: التوجيه الجغرافي، إنترنت الأشياء (IoT)، اتخاذ القرارات متعددة المعايير TOPSIS، (MCDM)، شبكات الاستشعار اللاسلكية (WSNs).