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ORIGINAL PAPER

Game-Theoretic Optimization of Energy-Efficient Multihop Routing and Clustering in Wireless Sensor Networks

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ABSTRACT

The lifespan of the Intelligent Transport System (ITS) nodes should be expanded, as overloaded nodes dying early affects existing hierarchical routing protocols, thus impacting the nodes lifetime. Inspired by this idea, an energy-efficient multipath routing method is proposed by utilizing adaptive clustering in wireless sensor networks (WSNs). A game-theoretic method for managing low energy multipath routing (LEMR-GT) in noncooperative games is developed to create energy-efficient network communication with equitable energy distribution. The utility function is based on the remaining power, amount of traffic, and number of links of nearby nodes. The contention radius for nodes is modified according to the topology and traffic load used to choose the cluster head. Then, the active nodes select the final cluster leader by assessing competitive parameters. Simulation results demonstrate that the proposed approach significantly outperforms conventional clustering protocols, such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and Hybrid Energy-Efficient Distribute, in terms of network lifetime, energy efficiency, packet delivery ratio, and end-to-end delay. The LEMR-GT results indicate that our method achieves up to 38% improvement in energy savings, a 25% increase in network lifetime, and over 15% higher packet delivery ratio.

Keywords: Energy clustering; Routing; Wireless sensor network.

INTRODUCTION

Wireless Sensor Nodes (WSNs) play a crucial role in Intelligent Transportation Systems (ITSs) by providing real-time data that enables efficient traffic management, enhances safety, and improves overall transportation infrastructure. The real-time information helps in ITSs including tracking targets, monitoring the environment, and conducting military surveillance. Effective and equitable energy use is crucial for prolonging network lifetime, which is a primary issue in ITS applications, as sensors commonly rely on batteries with limited lifespans. Topology control involves setting each sensor's transmission parameters to achieve the best network performance based on specific optimization criteria, such as network connectivity. The challenging issue of WSN topology is to maximize the lifetime of sensor nodes. One difficulty is that each sensor acts independently based on local topology information, prioritizing its own interests.

Wireless sensors integrated into intelligent transport system (ITS) is not fully optimized to reduce traffic accidents, improve accident survival, and maintain intelligent speed adaptation (Shaaban *et al.* 2021).

Game theoretic based traffic flow management, congestion pricing, route selection, and cooperative driving is discussed by Wang *et al.* (2022), highlighting the potential of game theory in addressing complex transportation problems. Xu *et al.* (2016)

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presented a game theory-based on multipath routing protocol for WSNs. The protocol aims to balance the energy levels of cluster heads and nodes. Different clustering algorithms utilizing game theory to optimize energy efficiency have been introduced in recent years for WSNs (Chakraborty *et al.* 2017; Goswami *et al.* 2022; Khan *et al.* 2023; Pandey and Pal 2014; Rajee *et al.* 2023). These methods prioritize choosing cluster heads efficiently but do not provide a comprehensive solution for the entire network. Traditional routing methods are not very practical for energy efficiency because the energy levels of nodes go down when choosing cluster heads (Afsar *et al.* 2019; Jing and Aida 2009; Wu *et al.* 2016). Furthermore, they do not prioritize the extensive distance of communication between nodes and the base station. Shang *et al.* (2014), Shi *et al.* (2012), and Sampath *et al.* (2024) do not consider remaining node energy when calculating best path.

Samuel *et al.* (2024) focused on congestion pricing, traffic signal control, route planning, and vehicle routing problems. They discussed how game-theoretic approaches can be used to design efficient and sustainable transportation systems, but energy consumption and delay were not considered. Creating clusters is a technique that enhances network energy efficiency by organizing topology. It is particularly beneficial in settings with a need for scalability ranging from hundreds to thousands of nodes (Laouid *et al.* 2017). This process includes choosing a small number of nodes as cluster heads—that are responsible for gathering information— that connect to other clusters and create clusters centered on them. Selecting the best cluster heads is the main obstacle, since it leads to lower energy usage for the entire network. A nature-inspired firefly algorithm is suggested for node clustering, incorporating a time division multiple access scheduler to reduce node energy usage and greatly extend the network lifespan (Maratha *et al.* 2021). A non-uniform clustering routing algorithm is suggested, which utilizes K-means clustering to select the best cluster heads by considering the radius parameter (Wang *et al.* 2019). A mathematical model for task dispatching is suggested to reduce total task completion time, determining the optimal dispatching rate to extend network longevity (Guo *et al.* 2015). Lately, game-theoretic methods have become the preferred option for researchers to select the best cluster heads during cluster formation.

Panchal and Singh (2021a) proposed a cost-effective topology design using noncooperative game theory to reduce network costs. cost refers to factors such as the resources required to establish a connection, route delay, the tendency of paths to become congested, and cluster weights. The weights are adjusted to maintain topology control by modeling active nodes as game players (Panchal and Singh 2021b).

The energy welfare and balance algorithm is proposed to manage node communication and data aggregation (Singh *et al.* 2024). The existing research have shown that the life of sensor nodes is extended as long as their service delivery remains stable. There is a need to extend network lifetime by developing energy-oriented routing protocols to reduce energy consumption (Elavarasan and Rajaram 2024; Roberts *et al.* 2024; Wan *et al.* 2024). The nodes should be applied with a fixed radius in the cluster formation. Many routing algorithms have already been discussed about the cluster formation and multipath routing, but they do not consider topology control or low energy multihop routing through a game-theoretic approach. This work formulate a noncooperative game-theoretic approach for low energy multihop routing with optimal clustering.

This paper proposes clustering-based multihop routing using game-theoretic approach, known as low energy multipath routing (LEMR-GT). The LEMR-GT plan operates in several rounds with two main parts: (i) a game-theoretic clustering system that selects best cluster head and (ii) a multihop routing system within and between clusters that takes into account energy considerations when determining the optimal path to the base station. Optimal cluster heads improve the network's lifetime by serving as a primary source of data transmission, thus maintaining network connectivity through other active nodes. The novelty of the work lies in the integrated mathematical game-theoretical framework that combines clustering and routing, which is different from the Energy-efficient Clustering Algorithm based on Game Theory (ECAGT) and traditional approaches. The method presented here optimizes both cluster head election and routing, which has not been focused on previous research. The scalability of this approach shows the stability of clusters and fairness in energy consumption.

The work is organized as follows: (1) cluster head selection depends on the competition parameters to prolong the network lifetime; (2) adaptive adjustment of clustering and cluster heads depends on the node survival, prolonging the life time of active nodes; (3) the LEMR-GT is formulated to develop multihop routing optimization to maintain energy consumption; and (4) proposing energy balance life maximization with low energy, multihop, routing-optimized clustering approach to routing in ITS.

Table 1 details the terms and notations are being used in the research.

Table 1. Nomenclature.

Symbol	Description
S	Set of sensor nodes
N	Maximum nodes
d_{ij}	Euclidean distance between the nodes
E_s	Sender's energy consumption
$E_T(l, d)$	Total energy model
E_R	The received data energy consumption
ε_{fs}	Power consumption per unit distance in free space model
ε_{mp}	Power consumption per unit distance in multipath model
h_{si}	Node hierarchy
d_{iToBS}	Distance between the i-th node and the base station
R_c	Communication radius
r_h	Competitive cluster radius
NE_{avg}	Average neighbour available energy
E_r	Residual energy
E_i	Initial energy
$Ri(p_i, E_r)$	Regret function
$\Gamma=\langle N, S, \{u_i\}\rangle$	Strategic game
N_N	Maximum number of neighbouring nodes
$p_i = (p_1, p_2, \ldots\ldots\ldots p_n)$	Sensor node's power profile

Source: Elaborated by the authors.

METHODOLOGY

A network of random sensor nodes is considered, whose primary purpose is to collect data for ITSs. The set of nodes are denoted as $S = \{s_1, s_2, \ldots\ldots s_N\}, |S| = N$ and the spatial points are coordinated using the Euclidean distance between the nodes (Eq. 1):

$$d_{ij} = \sqrt{(a_i - a_j)^2 + (b_i - b_j)^2} \tag{1}$$

The nodes are located in circular fashion with communication radius d_0 (Jing and Aida, 2009). The total energy model is shown in Eq. 2:

$$E_T(l,d) = \begin{cases} lE_s + l\varepsilon_{fs}d^2 & d < d_0 \\ lE_s + l\varepsilon_{mp}d^4 & d \geq d_0 \end{cases} \tag{2}$$

where E_S is the sender's energy consumption per l bits of data. The energy consumption at the receiver is as shown in Eq. 3:

$$E_R = lE_s \tag{3}$$

where ε_{fs} and ε_{mp} are the free space and multipath fading channel coefficients. $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ is the threshold value. When $d < d_0$, the free-space channel model is applied; otherwise, the multipath fading channel model is used.

The node hierarchy h_{si} is associated with base station (BS) distance d_{iToBS} and the communication radius R_c. The node hierarchy is shown in Eq. 4:

$$h_{s_i} = \frac{d_{iToBS}}{R_c} \tag{4}$$

Competition radius as cluster parameter

The uniform clustering can be formed by considering the cluster radius between different rings, and distance of the base station (Afsar *et al.* 2019), hence the competitive cluster radius is calculated as shown in Eq. 5:

$$r_h = \begin{cases} 0 & if\ h = 1 \\ \sqrt{\frac{1}{\pi d}} & if\ h = 2 \\ \sqrt{\frac{(2h-1)(k^2-1)}{3(k^2-h^2)+6h-3} \times \frac{1}{\pi d}} & if\ 2 < h \leq k \end{cases} \tag{5}$$

The upper limit of ring structure is k which is the topological constraint to identify the node's energy level.

Average neighbor available energy (NE_{avg}) as competition parameters

It is important to measure the average neighbor available energy in the cluster, the available energy, and the maximum average available energy level is updated (Eq. 6):

$$NE_{avg} = \frac{E_r/(N+1)}{E_i/(N_N+1)} \tag{6}$$

where E_r is the residual energy of the node, E_i is the initial available energy, N is the current number of neighborhood nodes in the current cluster, and N_N is the maximum number of neighboring nodes in the cluster.

Regret function as the competitive parameter

Every sensor must be connected to the base station to deliver a service packet in a network. However, due to energy cost, it fails to connect to the network. In this work, the regret function is introduced to limit an excessive transmit power (p_t) and a low residual energy (E_r). A specific regret function for node is calculated as shown in Eq. 7:

$$R_i(p_t, E_r) = \frac{1}{N_i}\int_{E_i-E_r}^{E_i-E_r+p_t} f_i(x)dx \tag{7}$$

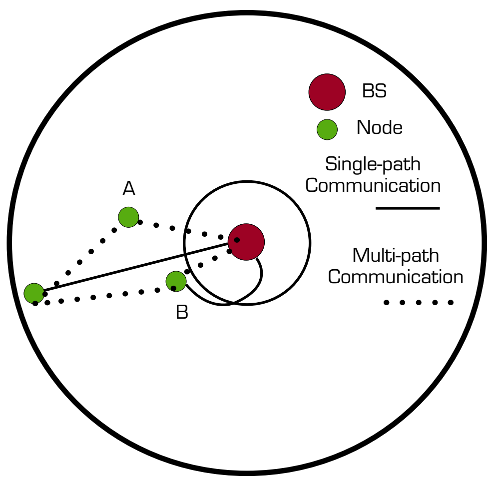
This equation represents the regret function in terms of transmit power and residual energy. There are three different cost function considered for $f_i\,(x)$: linear $f_i\,(x) = x$, quadradic $f_i\,(x) = x^2$, and exponential $f_i(x) = \exp(\frac{x}{10})$, which are taken for the pricing values as topology constraints.

CLUSTERING FORMULATION

The multihop clustering is chosen among the networks. Three communication cases are considered: In single-path communication (shown by solid lines), each node transmits data directly or through a single relay path to the BS, ensuring lower overhead but potentially reducing fault tolerance. On the other hand, multi-path communication (depicted with dotted lines) allows nodes, such as node A, to establish multiple alternative routes toward the BS through intermediate nodes like B, thereby enhancing reliability, load balancing, and fault tolerance at the expense of increased energy consumption and routing complexity as per the path structure (Wang *et al.* 2022). The node hierarchy in the cluster is formulated using Eq. 8:

$$CH = \begin{cases} \sum_{i=1}^{N} d_{Sn_i} d_{n_iR} & < \frac{nE_S}{\varepsilon f_s}, \quad SL \\ \sum_{i=1}^{N} (d_{Sn_i i})^2 - ({d_{Sn_i i}}^2 + {d_{n_iR}}^2) & < \frac{2nE_S}{\varepsilon f_s}, \quad NSL \\ \sum_{i=1}^{N} d_{Sn_i} d_{n_iR} + \sum_{i=1}^{N} (d_{Sn_i i})^2 - ({d_{Sn_i i}}^2 + {d_{n_iR}}^2) & < \frac{(n1+2n)E_S}{\varepsilon f_s} \quad CSL \end{cases} \tag{8}$$

Figure 1 shows the cluster formation with straight and non-straight line paths, with base station located at the center where A, B and C are randomly distributed. According to the protocol design, single- and multipath communication is explained. Here, d_{Sn_i} is the distance between the sender node and the relay node (d_{Sn_iR}). In the first case, the communication is chosen as single hop. The second case is multihop communication if in the non-straight line. In the third case, a combined path is selected when the route is neither straight nor non-straight. (Xu *et al.* 2016).



Source: Elaborated by the authors.

Figure 1. Clustering formation.

GAME THEORETIC OPTIMIZATION FORMULATION FOR MULTIPATH ROUTING

A noncooperative game was formulated describing the optimal clustering and LEMR. The players in a game are sensor nodes with transmit power p_i.

Here, $\Gamma = \langle N, S, \{u_i\} \rangle$ is a strategic game if the strategy tuple $s^* = (s_1^*, s_2^*, \ldots, s_n^*)$, the game desirable solution is Nash equilibrium (NE), and its utility function (UE) is solved by own strategy. A game may possess the NE point if it satisfies Eq. 9:

$$u_i(s^*) \geq u_i(s_i, s_{-i}^*) \tag{9}$$

For $\forall i \in N$ *and* $\forall s_i \in S_i$, the binary connectivity reward function satisfies the threshold, and additional redundant transmissions yield no extra benefit but increase regret. This helps stabilize the system by supporting cluster head formation and maintaining power efficiency.

The set of strategies is described by the nodes of the set with different power levels: $S_i = [0, p_i^{max}]$. Each sensor node must choose the power from the power profile $p_i = (p_1, p_2, \ldots, p_n)$. This indicates that the construction depends on the available energy.

Therefore, the sensor node must consider the competitive parameters while forming the clusters and reduce the regret function in order to maximize the benefit received by the sensor node. The benefit or revenue of the game is generated by using Eq. 10:

$$\varphi_i(\Gamma) = H\Lambda\,(p_i) \tag{10}$$

where $H\Lambda(p_i)$ is the node hierarchy indicator of strategy power profile. The strategy should be $\Lambda = \{p_i : a(\Gamma) > \delta$, where δ is a weighting parameter representing the connectivity redundancy. The utility or revenue function is reformulated as Eq. 11:

$$u_i(p_i) = \varphi_i(\Gamma) - R_i(p_t, E_r) \tag{11}$$

The utility function regulates the network connectivity without any redundant information and reduces the regret function to maintain low energy and optimized clustering approach. The nodes act as players that choose the transmission power to ensure the existence of NE.

Hypothesis 1: The strategic game $\Gamma = \langle N, S, \{u_i\}\rangle$ whose function is denoted as Eq. 12:

$$V(p_i, E_r) = h\Lambda\,(p_i) - \frac{1}{N}\int_{E_i - E_r}^{E_i - E_r + p_t} f_i(x)dx \tag{12}$$

The proof is derived for the understanding of NE existence. Each player's strategy set is denoted as $i \in V, p_{-i} \in S_{-i}$ and there are two possible strategies: $p_i, q_i \in S_i$. The difference in utility reflects that preference from p_i, to q_i and have the same sign if p_i, $> q_i$, meanwhile the regret function $R_i(p_i, E_r) > R_i(q_i, E_r)$ inequality implies that players would feel more regret for reducing this strategy level.

The difference in utility function is shown in Eq. 13:

$$\begin{aligned} \triangle u_i &= u(p_i, p_{-i}) - u(q_i, p_{-i}) \\ &= H\Lambda\,(p_i, p_{-i}) - H\Lambda\,(q_i, p_{-i}) + R_i(q_i, E_r) - R_i(p_i, E_r) \end{aligned} \tag{13}$$

The difference $\triangle H = H\Lambda\,(p_i, p_{-i}) - H\Lambda\,(q_i, p_{-i})$ is equal to 1 if $(p_i, p_{-i}) \in \Lambda$; and equal to 0 if $(p_i, p_{-i}) \notin \Lambda$.
From constraint $\triangle H \in \{-1, 0, +1\}$ and monotonic $\triangle R_i$

$$\triangle u_i = \underbrace{H\,(p_i, p_{-i}) - H\,(q_i, p_{-i})}_{\in \{-1,0,+1\}} + \underbrace{R_i(q_i, E_r) - R_i(p_i, E_r)}_{\triangle R_i}$$

If both (p_i, p_{-i}) and (q_i, p_{-i}) lie in Λ or both out of Λ $(\triangle H = 0)$, *then* $\triangle u_i = -\triangle R_i$ and $sgn\,(\triangle u_i) = sgn\,(-\triangle R_i)$
If $(p_i, p_{-i}) \in \Lambda$ and $(q_i, p_{-i}) \notin \Lambda$, then $\triangle H = +1$ and $\triangle u_i) = 1 - \triangle R_i$.
If $(p_i, p_{-i}) \notin \Lambda$ and $(q_i, p_{-i}) \in \Lambda$, then $\triangle H = -1$ and $\triangle u_i) = -1 - \triangle R_i$.

This reproduces a piecewise sign map in the solution. The solution of the game is shown in Eq. 14:

$$sgn(\triangle u_i) = \begin{cases} < 0 & (p_i, p_{-i}) \in \Lambda, (q_i, p_{-i}) \in \Lambda \\ < 0 & (p_i, p_{-i}) \notin \Lambda, (q_i, p_{-i}) \notin \Lambda \\ \geq 0 & (p_i, p_{-i}) \in \Lambda, (q_i, p_{-i}) \notin \Lambda \end{cases} \tag{14}$$

Therefore, the game has proved NE for the network connectivity and adaptively adjusts the transmit power in terms of residual energy. The players have chosen transmit powers from the set which is at low level to maintain the residual energy.

The LEMR-GT algorithm focuses on nodes with low energy levels. A clustering approach is employed that prioritizes cluster heads with compatible nodes, aiming to prolong the lifespan of low-energy nodes. Considering any participating node as S_i, it determines its competitive radius r_h according to its hierarchy h. Voting depends on the competitive nature of the radius to avoid contradictions. The votes are calculated to avoid repetitive nodes with excessive votes; each node is limited with the MaxVote option to avoid repetitive nodes based on their energy levels. To gather routing decision-making data, sensor *i* starts by setting its transmitting power to the highest level (p_{max}) and identifies its neighboring sensors (*Ni*) by sending a "Neighbor Request Message" and receiving responses at power level (P^*j). After receiving a successful message and weighting parameter δ, the list of neighbors is updated in the game (Table 2).

Table 2. LEMR-GT algorithm: pseudocode for clustering and routing process.

Functions	Algorithm procedure
Input	Set of sensor nodes S $S = \{s_1, s_2, \ldots s_N\}$, Power Profile $p_i = (p_1, p_2, \ldots p_n)$, δ
Output	Set of cluster Heads
Initialize	CH formation if $h_{si} > 1$ then
	S_i Broadcast cluster_msg (r_h, NE_{avg} Pi, R_i (p_i, E_r)) cluster head is selected based on Eq. 8
	Else
	Distribute the nodes into cluster head based on topology constraints
While	Receive_msg to form cluster do
	if $h_{si} = h_{sj}$ then check if $d_{ij} < r_h$, then Add S_i to S_j as neighbours end end
Initialize	Routing based on game theory

Ensure	Choose a power according to NE
	$\Lambda = \{p_i: a(\Gamma) > \delta$ then check optimal power using equation (10)
	$P^* = arg\ max\ u_i(p_i, p_{-i})$
	Check if P^* is not an NE and $\Lambda = \{p_i: a(\Gamma) > \delta$
	then
	$N_i = N_i + 1$ end if
	else
	update u_i (p_i) using equation (11)
	end if

	end while return p^*

Source: Elaborated by the authors.

The received power of request is calculated by using the reply message from the neighborhood nodes (Wang *et al.* 2022). Its optimal power level (P^*) is assured to determine the connectivity among all nodes and reduce the transmit power between nodes. Using the neighbor lists that have been gathered, sensor *i* is able to understand the local structure the game and ensure the existence of NE.

EXPERIMENTAL RESULTS AND DISCUSSION

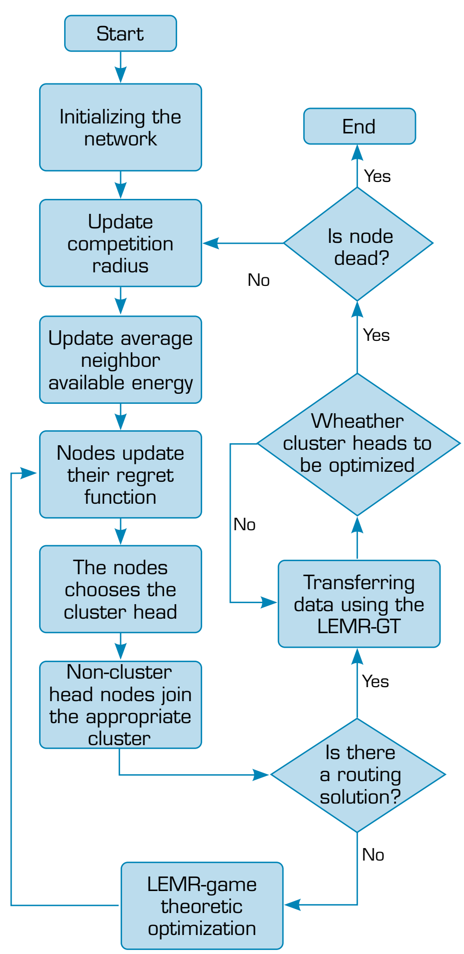
The experimental results are simulated using the MATLAB platform to illustrate the deployment of a WSN with cluster head and sensor nodes with competitive radius, showing data transfer using LEMR-GT. The deployment of cluster head and sensor nodes are distributed over an area of 200 × 200 m^2. The distance range and initial energy are set as d_{max} = 150 m and E_i = 0.5 J, respectively. The minimum power of link communication is $p_{min} = 7\times10^{-10}$ W, and the communication radius d_0 with the signal capture threshold is 100 m, with a frequency of f = 2.5 GHz (Wang *et al.* 2022).The transmission packet size is m = 4,000 bits, with rate of 106 bits s^{-1}. The detailed list of simulation parameters is given in Table 3.

Table 3. Simulation parameters.

Parameters	Value
Total number of nodes	1000
Base station position	800,800
Sensing area	200x200 m2
Initial energy	.5 J
d_{max}	150 m
d_{th}	100 m
M	4,000 bits
p_{min}	7×10^{-10} $Watts$
ϵ_{mpl}	0.0013 $pj/bit/m^4$
Carrier frequency	2.5 GHz

Source: Elaborated by the authors.

The LEMR-GT algorithm procedure is detailed in the flowchart shown in Fig. 2. As stated earlier, clustering and routing are done in consecutive phases. Figures 3 and 4 show the network node cluster formation and routing hierarchy of nodes. Competition parameters, such as competition radius, neighbor node energy, and regret function, are important in cluster formulation and routing game strategy. Previous clustering techniques, such as Low-Energy Adaptive Clustering Hierarchy (LEACH) existing game theory, saw the nodes' average residual energy reaching 0 after 3,000 rounds.



Source: Elaborated by the authors.

Figure 2. Flowchart of LEMR-GT algorithm.

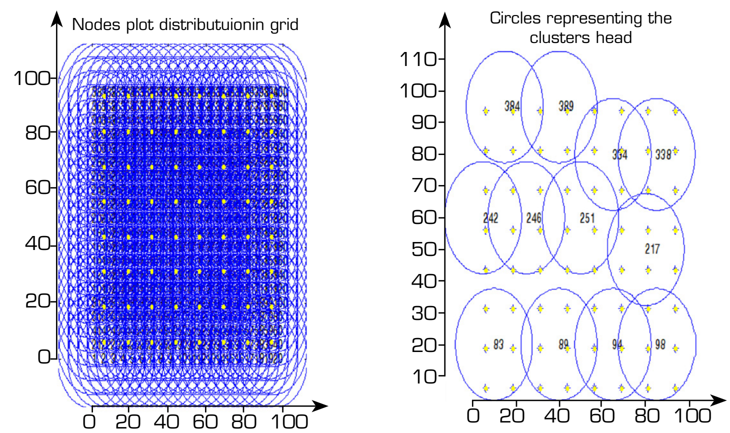


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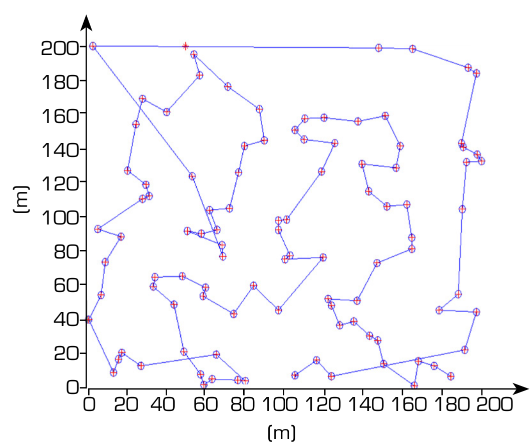
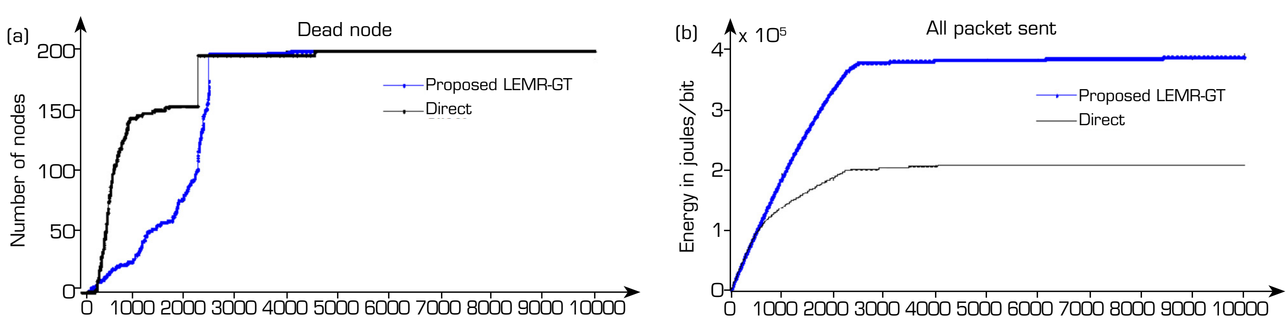
Figure 3. Simulation of Proposed WSN using competitive radius.



Source: Elaborated by the authors.

Figure 4. Network routing.

In Fig. 5a and 5b, when the remaining energy decreases, a sensor's reluctance increases linearly with the use of linear pricing; and it rises gradually in the initial phase of the network's lifespan when exponential pricing is used. This observation suggests that the topologies generated by the lifetime-extending topology control, using the linear function, prioritize energy balance, whereas those with exponential function prioritize energy efficiency. Hence, a quadratic pricing function is utilized in our utility function to incorporate the game, serving as a compromise between energy balance and energy efficiency.



Source: Elaborated by the authors.

Figure 5. (a) average number of dead nodes; (b) residual energy.

Figures 6 and 7 assess the network's total energy dissipation and lifetime over 5,000 rounds. Different clustering protocols result in varying numbers of packets successfully reaching their intended destinations. The minimum number of packets transferred by the LEACH protocol is 39,763.

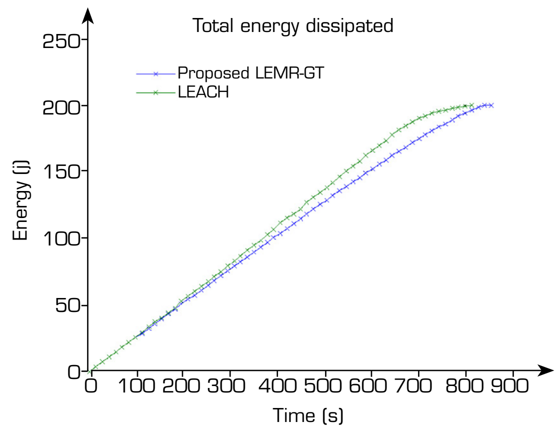


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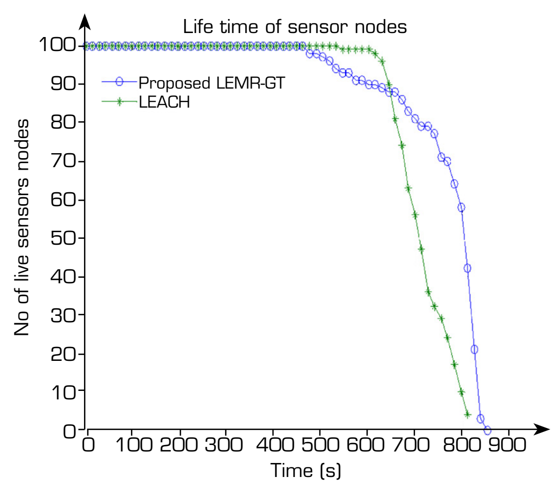
Figure 6. Total Energy dissipation.



Source: Elaborated by the authors.

Figure 7. Lifetime of sensor nodes.

Energy-efficient game theory-based clustering, cross-layer clustering, localized game-theoretical clustering algorithm, and ECAGT have reported 40,987, 50,974, 62,874, and 63,078 transmission packets, respectively. The proposed LEMR-GT outperforms LEACH, PEGASIS, and existing ECAGT protocols with a longer lifetime of nodes transferred in 5,000 rounds. These findings indicate that LEMR-GT sends an increased number of packets compared to LEACH, PEGASIS, and existing ECAGT protocols (Xing *et al.* 2021).

This distinction guarantees that LEMR-GT has chosen a more efficient route for data transfer than current methods, which ultimately results in a higher success rate of packet transmission to the base station. The comparative results are presented in Figs. 8–10 to demonstrate effectiveness.

From the comparative analysis of dead nodes shown in Figs. 8–10 and Table 4, the proposed algorithm demonstrates improved coverage and lower power consumption in WSN deployment. When the number of nodes reaches 50, there is a 7% difference in coverage percentage between the proposed algorithm and the existing approach in terms of energy. When the number of nodes

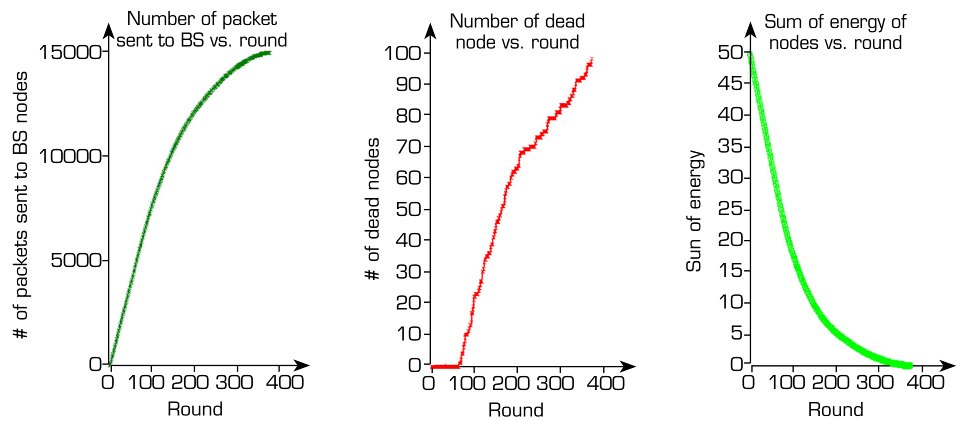


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Figure 8. Comparative analysis of dead nodes.

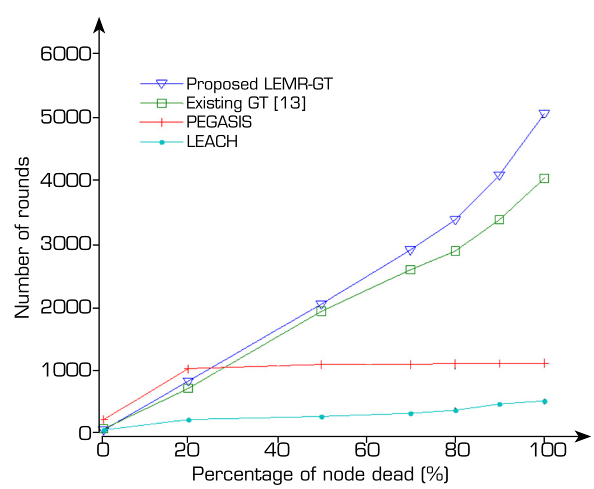

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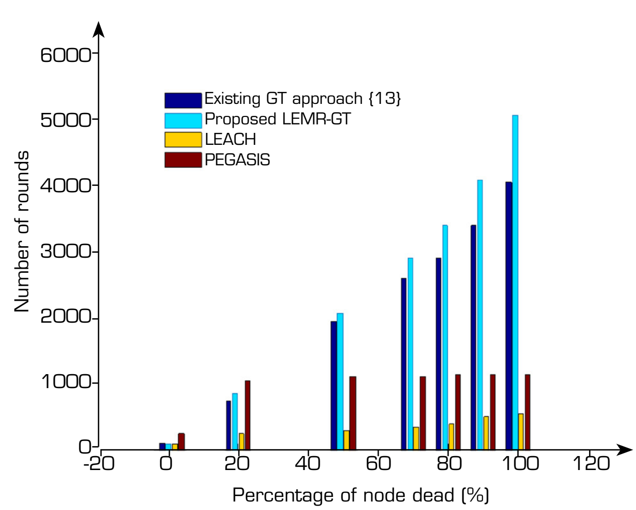
Figure 9. Comparative analysis of dead nodes with other methods.



Source: Elaborated by the authors.

Figure 10. Comparative analysis of dead nodes.

Table 4. Comparative analysis of parameters.

Contributors	Algorithm	FND (rounds)	HND (rounds)	LND (rounds)	Energy consumption (for 100 nodes)	Number of alive nodes (for 100 nodes)
Goswami *et al.* (2022)	Self-organizing map	4,300	3,300	2,200	400 mJ	15
Gupta *et al.* (2022)	LEACH and game theory	4,467	3,742	3,279	0.5 J	18
Panchal *et al.* (2021b)	Energy efficient selection of Cluster Head and Grid Head (EOCGS)	641	796	823	43 J	20
Proposed work	LEMR-GT	5,000	2,400	873	120 J	24

Source: Elaborated by the authors.

reaches 100, the coverage performance remains high, indicating the suitability of the proposed approach for resource-constrained applications with a prolonged lifetime. The larger network size further highlights its efficiency in extending the WSN lifespan.

The dead nodes percentage reaches 50% when the number of rounds is 2,200 and reaches 100% when the number of rounds is 5,500, as indicated in Fig. 10, showing the prolonged lifetime of WSN nodes.

CONCLUSION

The proposed LEMR-GT algorithm works well for cluster head formation and data transmission under low residual energy, significantly enhancing the network's efficiency and reliability in comparison to existing protocols. Furthermore, cluster formation involves a thorough analysis of various network parameters, leading to enhanced energy efficiency through optimal selection of cluster heads and determination of the most efficient data transmission path. Several tests were carried out with MATLAB to evaluate the efficiency of the new plan artificially created.

The LEMR-GT scheme outperforms current clustering protocols, such as LEACH and PEGASIS, while the existing ECAGT protocols show no improvement. Evaluation of its energy efficiency in the comparative analysis considers the remaining energy of nodes, dead nodes, and network capacity. Furthermore, additional advancements are observed in terms of network lifetime, total energy dissipation, and average energy. These strategies are applied consistently in modern clustering algorithms.

Possible new diverse elements could be integrated into game-theoretic clustering models along with other facets of network configuration. It is feasible to create clustering and routing algorithms by utilizing sparse matrices, as they provide a more effective method to aggregate data.

CONFLICT OF INTEREST

Authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

Conceptualization: Kothapalli K; **Methodology:** Kothapalli K; **Validation:** Abraham N; **Formal analysis:** Kothapalli K; **Writing – Original Draft:** Kothapalli K; **Writing – Review & Editing:** Abraham N; **Supervision:** Abraham N; **Final approval:** Abraham N.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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