https://africanjournalofbiomedicalresearch.com/index.php/AJBR
Afr. J. Biomed. Res. Vol. 27(6s) (December 2024); 101-108
Research Article

Hybrid Optimization Approach for Energy-Efficient Routing (HOAER) In Wireless Sensor Networks: A Case for Forest and Agricultural Monitoring

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Abstract: In wireless sensor networks (WSNs), the design of energy-efficient routing protocols is critical due to the constrained energy resources of sensor nodes. To address this challenge, we propose the Hybrid Optimization Approach for Energy-efficient Routing (HOAER), which leverages a hybrid Ant Lion Optimization-Genetic Algorithm (ALO-GA) framework to optimize cluster formation. For a given number of clusters, the ALO-GA optimization generates distinct θ\thetaθ values to ensure a balanced distribution of nodes across all clusters. HOAER introduces a Cluster Head (CH) Eligibility Rule to enhance energy efficiency. Eligible nodes within a defined distance from the cluster center are considered for CH selection, with the node possessing the highest residual energy chosen as the CH. If no eligible nodes are found, a fallback mechanism selects the node closest to the base station as the CH. The protocol employs a hierarchical data routing mechanism, where member nodes transmit data to their CH, which aggregates and forwards it to the base station. This integration of ALO-GA optimization with hierarchical routing significantly minimizes energy dissipation and prolongs the network's operational lifespan. Simulation results demonstrate that HOAER outperforms existing state-of-the-art protocols in terms of energy efficiency, network longevity, and data delivery. Moreover, HOAER's applicability extends to real-world scenarios such as forest and agricultural monitoring. For instance, the protocol can be deployed in forests for tracking wildlife movements and predicting early fire alarms, or in agricultural fields for monitoring soil conditions and crop health, offering practical utility in resource-constrained environments.

Keywords: Ant Lion Optimization-Genetic Algorithm, Cluster Head, Energy-efficient Routing, wireless sensor networks,

Received: 08/12/2024 *Accepted: 13/12/2024*

DOI: https://doi.org/10.53555/AJBR.v27i6S.5280

I. Introduction

The area of Wireless Sensor Networks (WSNs) has recently drawn great attention because of its various applications in fields such as environmental monitoring [1-3], military surveillance and smart cities [4-6]. These networks consist of spatially distributed sensor nodes that collect and transmit data often in harsh or remote environments [7]. The key problem in WSNs is related to the energy resources for sensor nodes, which are typically powered by batteries with non-renewable energy sources. Hence, designing an energy-efficient routing protocol which minimizes energy consumption with reliable data delivery is significant for extending the lifespan of the network and improving its performance [8-9].The present article therefore postulates a new energy-aware routing protocol named the Hybrid Optimization Approach for Energy-efficient Routing (HOAER), which uses a hybrid Ant Lion Optimization-Genetic Algorithm (ALO-GA) framework for optimizing clusters of the network. It has the hybrid nature of the algorithm, where it utilizes the strength of both the Ant Lion Optimization and Genetic Algorithms to obtain an optimal balance and efficiency of node distribution across clusters. Ensuring the formation of the clusters is optimal, HOAER ensures a drastic reduction in energy consumption, which is crucial for the longevity of the network.One of the unique features of HOAER is its Cluster Head (CH) Eligibility Rule, in which nodes within a predefined distance from the cluster center are evaluated for the role of CH [10-12]. The selection of the CH is based on the remaining energy of the candidate nodes, ensuring that the most energy-efficient node is chosen to handle the communication tasks for the cluster[13]. Moreover, HOAER also has a fallback mechanism whereby even if no suitable nodes are available, a proper CH is chosen according to proximity to the base station. Most of the researchers also proposed a Power-Efficient Cluster-based Routing (PECR) algorithm that uses clustering and introduces a Main Cluster Head to optimize energy consumption and promote network lifetime, but did not specifically address the problem of a two-level tree-based clustering approach [13-14]. The proposed two-level clustering chain routing protocol enhances energy efficiency in heterogeneous wireless sensor networks based on the selection of the cluster head, using a method that considers remaining energy and distance to the base station, which outperforms PEGASIS and SEP in terms of consumption, life cycle, and throughput [15]. Some researchers proposed mayfly-aquila optimization algorithm [16] and coyote Optimization technique [17-18] for improvement in clustering and routing. While [19-22] paper proposed GABEER algorithm to improve energy efficiency in wireless sensors

In order to further improve energy efficiency, HOAER adopts in each cluster a multi-chain routing mechanism, where sensor nodes forwarded data to their designated CH, the CH forwarded aggregated data to the base station[23-25], which makes the hierarchical structure of routing combined with ALO-GA optimization that leads to effective reduction in energy consumption by the network.

The simulation results show that HOAER outperforms existing protocols in terms of energy efficiency, network longevity, and data delivery reliability. This proposed protocol not only deals with the critical issue of energy consumption but also contributes to developing more sustainable and robust wireless sensor networks for a wide array of applications.

The structure of this study is organized as follows:
Section I presents the introduction and literature review, in which we discuss existing energy-efficient routing protocols in wireless sensor networks and identify the challenges they address, especially in terms of energy consumption and network longevity.

In **Section II**, we introduce the system model used in our research, providing the foundational framework for our analysis.

Section III provides the full explanation of the EE-TLT protocol, illustrating its structure and functioning model. Results of the simulations are depicted and analyzed for their full extent in **Section IV** to assess the efficacy of the proposed protocol. Finally, we summarize and conclude the study, outlining major findings and implications of overall results of the study in the conclusion drawn in **Section V**.

II. Proposed System Model

A. Network Model

All the sensor nodes, in the homogeneous network model, have the same attributes and initial energy level. Sensor nodes are distributed at random in a two-dimensional area of B square meters in such a way that it is approximately an equal number of nodes which lie within unit area. One BS represented by red colored square is placed at one fixed position far away from nodes.

The total initial energy of the network [26] is given by:

$$E_{init} = x.M \qquad (1)$$

where M is the total number of sensor nodes, and x is the initial energy of each sensor node. In this case, all nodes have the same energy level x, representing a homogeneous network setup.

The network is partitioned into clusters using the angular thresholds (∅) optimized by the ALO-GA algorithm. The thresholds describe sectors radiating from the geometric center of the network, as illustrated in **Figure 1**. The number of clustersk_c , is optimized to lie between 4 and 6, depending on the distribution of the nodes. In a cluster, the nodes inside it are in charge of sending their data to their respective cluster head, which collects the data from the member nodes and forwards them to the BS.

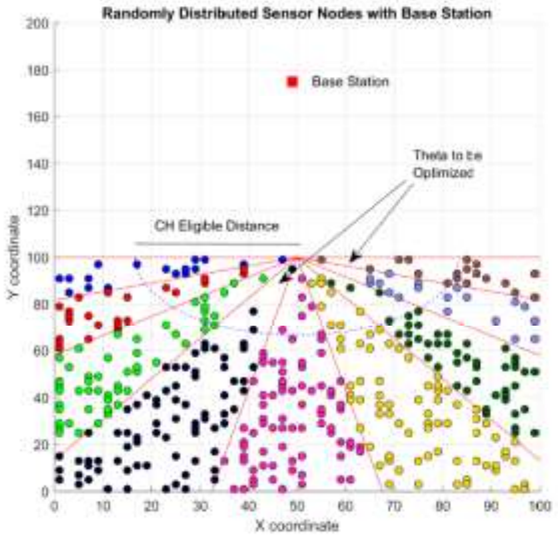

Figure 1 Distribution of nodes

The eligibility of a node to be a CH is determined by a distance criterion, *r*, from the center of the network. All nodes within this distance are eligible for selection as a CH. of the eligible nodes, the one with the highest residual energy is selected as the CH. If no node meets the eligibility criteria, the fallback mechanism selects the node closest to the BS as the CH [27-29].

The average area occupied by each sensor node is expressed as:

$$B_{node} = \frac{B}{M} \qquad (2)$$

Where B represents Total area of the network where sensor nodes are deployed and M are total number of sensor nodes in the network

and the average area of a cluster is:

$$B_{cluster} = \frac{B}{k_c} \qquad (3)$$

kc are number of clusters formed in the network,

The maximum distance from a CH to the farthest node within a cluster, assuming the CH is centrally located, is given as:

$$r_{max} = \frac{\sqrt{B}}{\sqrt{k_c \pi}} \qquad (4)$$

Nodes periodically observe their environment and transmit data to the BS via CHs using a multi-chain hierarchical routing mechanism. This approach, combined with optimized angular thresholds and the CH eligibility criteria, ensures energy-efficient communication, and prolongs the network's operational lifetime. Figure 2 shows the overview of HOAER protocol.

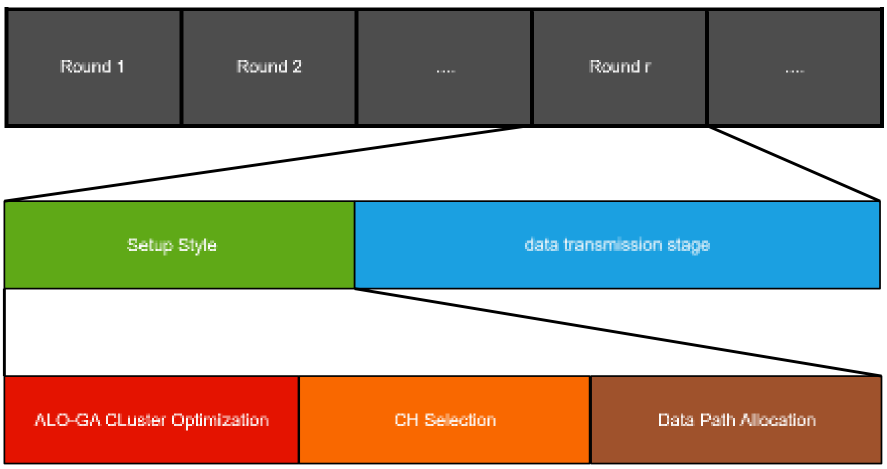

Figure 2 Division of HOAER Protocol

B. **Energy Consumption Model**

We use the same model used in previous works for energy depletion during the packet transmission by sensor nodes [30-32]. If there is a node which will send *q*-bit data at distance *d* to another node, the radio of node will use the following energy:

$$E_{Tx}(q,d) = \begin{cases} q.(E_{elec} + E_{fs}.d^2)\ if d < d_0 \\ q.(E_{elec} + E_{mp}.d^4)\ if d \geq d_0 \end{cases} \quad (5)$$

In this expression:

- E_{elec} represents the energy consumed by the transmitter or receiver's electronic circuits.
- E_{fs} and E_{mp} correspond to the energy amplification required for the transmission in the free space (d^2) and the multi-path (d^4) propagation models, respectively.
- d_0 is the threshold distance, which determines the transition between the two propagation models and is calculated as:

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}} \quad (6)$$

For receiving a data packet containing q-bit, the energy consumed by the receiver is given by:

$$E_{Rx}(q) = q.E_{elec} \quad (7)$$

This model allows for calculation of energy consumption based on transmission distance and the propagation model used in the environment.

III. **Proposed Approach**

The proposed work of Hybrid Optimization Approach for Energy-efficient Routing (HOAER) designed to improve the performance of wireless sensor networks (WSNs). The approach aims to enhance the network's efficiency by carefully managing the energy consumption of sensor nodes while ensuring reliable data transmission. The HOAER strategy is based on a multi-stage process that includes optimal cluster formation, intelligent cluster head selection, and an efficient data routing mechanism to the base station. The following subsections represents each of these critical stages that work together to achieve energy-efficient communication in the network.

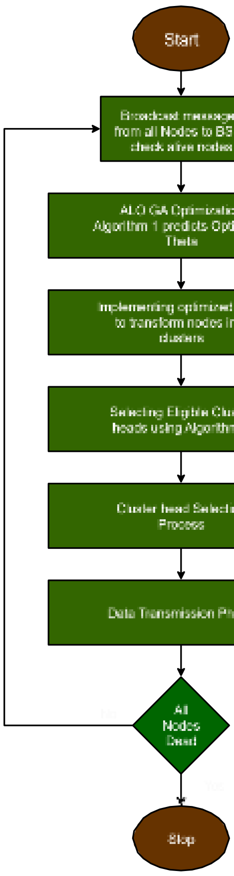

Figure 3 Flow chart of Proposed Approach

A. Cluster Formation

Our approach uses the Hybrid Optimization Algorithm (ALO-GA) to form the clusters, which is an optimization algorithm that combines ALO and GA for the optimization of angular thresholds θ's defining the sectors of the network. It helps in balancing the number of nodes in each cluster and thus contributes to better energy utilization and overall performance of the network. The process begins with partitioning the whole network into different logical sectors or clusters that can be represented by different angular thresholds. It guides the optimization using a fitness function that is based on the minimization of node imbalance across clusters. The steps for the ALO-GA optimization are depicted in Algorithm 1. The overall objective is to balance nodes in each sector, and thus ensure the fair division of nodes among sectors to reduce energy differences.

Algorithm 1: ALO-GA Optimization for Cluster Partitioning
Input: Number of clusters N_c, number of (max $\_iter$), Population size (P) and network parameters

Output: Optimized $\Theta = \{\theta_1, \theta_2, \ldots, \theta_{N_c}\}$ for cluster divisions.

1. **Initialize the population:** Randomly generate P initial solutions $\Theta^{(t-0)} = \{\theta_1{}^{(t-0)}, \theta_2{}^{(t-0)}, \ldots, \theta_{N_c}{}^{(t-0)}\}$, where $\theta_i \in [\frac{0,360}{Nc}]$.
2. **Evaluate fitness:** For each lion position (solution), compute the fitness value using the fitness function
$F(\Theta) = \sum_{i=1}^{i=Nc} |(\frac{N}{N_c}) - Cm_i|$ (8)

Where N is the total number of sensor nodes, N_c is the number of clusters, and Cm_i represents the cluster member of the i^{th}cluster.

3. **Set Initial elite:** Assign the best solution (minimum fitness value) as the elite solution
$\Theta_{elite} = arg_{\Theta \in Population} minF(\Theta)$
4. **Begin iterations:**

for $t = 1\ to\ maxiter$

For each ant solution:

- Update the position of ants using ALO equations:
- $\Theta^{(t-1)} = random\_walk(\Theta_{elite}, \Theta_{Current})$

Where random walk simulates the movement of ants in the search space.

- Apply crossover and mutation (Genetic Algorithm Step):

$\Theta_{mutated}^{(t+1)} = crossover(\Theta^{(t+1)} + mutation(\Theta^{(t+1)})$.

5. **Evaluate updated fitness values:**

Calculate $F(\Theta^{(t+1)})$ for all ants.

6. **If a new ant solution improves fitness:**

$\Theta_{elite} = arg_{\Theta^{(t+1)} \in Population}\ minF(\Theta^{(t+1)})$.

7. **Check stopping criteria:**

If $t = maxiter$ of fitness coverages ($F(\Theta_{elite}) \leq \in$), stop the process.

8. End for
9. **Return final optimized solution:**

$\Theta_{final} = \Theta_{elite}$

For the experimental setup, we use a network consisting of 100 sensor nodes distributed randomly within a 100x100 meter area[10]. The base station (BS) is located at coordinates (49,175).The algorithm optimizes the angular thresholds for dividing the network into clusters, taking into account the position of each node and the BS. These optimized thresholds help in forming balanced clusters, which are critical for ensuring efficient communication and energy consumption within the network.

B. Cluster head selection

The CH token rotation, which is periodically undertaken to address the hotspot problem, is also used to ensure equalized energy consumption among sensor nodes. This ensures that all eligible nodes have an opportunity to serve as CH, effectively distributing the load across the network. The eligibility for a node to become a CH is determined using a distance threshold denoted as CH_{th}, which is set as one-third of the maximum distance between the center of the cluster and the farthest node within the cluster. Nodes located within this threshold distance are marked as eligible cluster heads (CH_Es).The node that holds the highest residual energy within the CH_Es, the CHE will be a CH for this round is selected. In this strategy, communication can be highly energy-efficient since nodes using higher amount of energy resources are selected. However, if no node is a CH_Es in a particular cluster, a fallback mechanism is applied wherein the node closest to the BS is selected as the CH. This distance-based selection ensures continuous and reliable cluster head functionality even when no node is eligible.The detailed steps of the cluster head selection process are outlined in the accompanying algorithm, which also includes the mathematical representation of the CH_{th} calculation and the energy-based selection criteria. Equation 9 is used for calculating cluster heads.

$$CH = \begin{cases} argmax(E_{residual})\ if\ CH_E > 0 \\ argmin(Distance\ to\ BS)\ if\ CH_E \leq 0 \end{cases} \quad (9)$$

C. Data Routing

In the proposed approach, all Cluster Heads (CHs) directly send their aggregated data to the Base Station (BS). The data transmission within each cluster is handled through a chain-based approach with a combination of Dijkstra's Algorithm, where Cluster Members (CMs) sequentially forward their data to the Cluster Head (CH). This minimizes the distance and energy consumption for data transmission from individual nodes to the CH. After aggregation of data at the CH, it sends the aggregated data to the Base Station (BS). The algorithm selects the path with the minimum energy cost, considering the distance between each hop and ensuring minimal energy consumption for the overall data transmission process.This combined approach of chain-based communication and Dijkstra's Algorithm within clusters helps reduce the consumption of energy, and the network would have greater efficiency and longer lifespan.

IV. Simulation and Performance Evaluation

This performance is tested through the extensive simulations for determining the efficiency of the proposed approach in terms of optimization of energy consumption and network lifetime. Various performance metrics are used for complete analysis of the behavior of the network. These metrics reflect the good adaptation of the system to the dynamic nature of WSNs, which focuses on the energy dissipation, node activity, and overall stability of the network. The following sections describe the performance metrics used to measure the results, followed by an analysis of the experimentation results.

Performance Metrics

1. Energy Dissipation ($E_{network}$): The total energy consumed by all participating sensing nodes throughout the network's operation is calculated. It reflects the efficiency of the network in terms of energy usage, where lower energy dissipation signifies better performance. The energy dissipation can be computed as:

$E_{network} = \sum_{i=1}^{Nround} E_{total}$ (for all rounds) (10)

2. Ratio of Living Nodes to Rounds: This metric tracks the proportion of active or "living" nodes over the course of network operation. It quantifies the survival rate of nodes throughout the network's lifetime. The ratio of living nodes to rounds can be calculated as:

Ratio of Living Nodes to Rounds = $\frac{\text{Number of Living Nodes at round } r}{\text{Total Number of Nodes}}$ for each round r

Where:

- Number of Living Nodes at Round r is the count of nodes that are still operational at a particular round r,
- Total Number of Nodes is the initial number of sensor nodes deployed in the network.

A higher ratio indicates that greater number of nodes are active for longer time, which implies better network longevity and energy efficiency.

3. FND (First Node Dead), HND (Half Nodes Dead), and LND (Last Node Dead): These metrics measure the critical milestones of the network's lifetime:
   - FND: The round in which the first node dies, which indicates the initial failure in the network.
   - HND: The round when half of the nodes are dead, reflecting the mid-point of the network's operational lifetime.
   - LND: The round when the last node dies, representing the end of the network's functionality.

These metrics offer a comprehensive picture of the energy efficiency and operational lifespan of the network, which is essential for evaluating the performance of the proposed approach.

V. Experimentation Results and Analysis

This section presents the experimental results for the proposed Hybrid Optimization Approach for Energy-efficient Routing (HOAER) in Wireless Sensor Networks and makes a comparison against state-of-the-art protocols, namely EE-TLT[28], STDC[18], LEACH-VA[14], and PEGCP[16]. The results demonstrate the advantages of HOAER in terms of energy consumption, the ratio of living nodes, and key network performance metrics like First Node Dead (FND), Half Nodes Dead (HND), and Last Node Dead (LND).

For the experimentation, we use the network parameters as mentioned in Table 2. The simulation was conducted based on these parameters to evaluate the performance of HOAER against the aforementioned protocols.

- Ratio of Living Nodes: The HOAER performs superior over other protocols in the network. The proposed technique displays improved maintenance of active nodes of a system for a longer duration. EE-TLT, STDC, LEACH-VA, and PEGCP all seem inferior compared to the suggested methodology in terms of living ratio of nodes. In addition, HOAER showed a better improvement ratio as compared to EE-TLT, STDC, LEACH-VA, and PEGCP by 3.6%, 15.2%, 34.1%, and 15.2% respectively.
- Energy Consumption: HOAER is also more energy-efficient. The network consumes less energy during the operation compared to the protocols mentioned above. In terms of energy dissipation, HOAER reduces energy consumption by 3.2%, 18.3%, 20.4% and 16.3% compared to EE-TLT, STDC, LEACH-VA, and PEGCP, respectively.

The comparison results for FND, HND, and LND are presented in Table 1 (insert the table number for FND, HND, and LND data). As seen from the table, HOAER improves the time to the first node dead (FND), half nodes dead (HND), and last node dead (LND) when compared to the other protocols. HOAER shows better performance with a delay in FND, HND, and LND indicating a longer network lifetime.

Table 1 Comparison results for FND, HND, and LND

	FND	HND	LND
PEGCP	650	1250	1790
LEACH-VA	400	1075	1797
STDC	790	1250	1790
EE-TLT	803	1390	1801
HOAER	810	1440	1805

To further illustrate these improvements, refer to Figure 4 and Figure 5, which provide visual comparisons of the performance of HOAER against EE-TLT, STDC, LEACH-VA, and PEGCP. These figures clearly demonstrate the superiority of the proposed approach in terms of both energy consumption and network longevity.

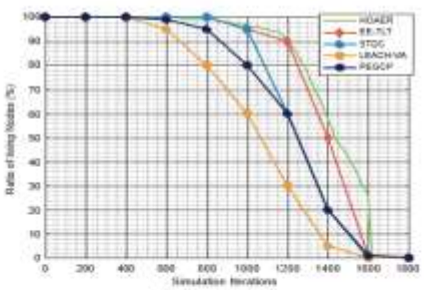

Figure 4 Trend of living Nodes over iterations

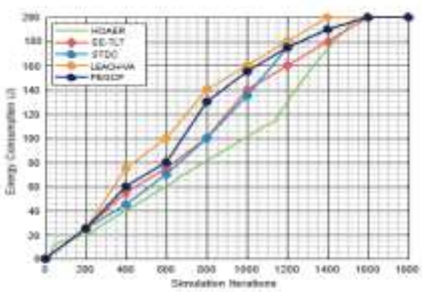

Figure 5 Energy consumption over Iterations

THE SIMULATION SCENARIOS INVOLVED VARIOUS PARAMETER VALUES

Symbol	Parameters	Value
A	Simulation area	100×100 m^2
N	Number of micro-sensor nodes	100 nodes
E_{friis}	Energy amplification for free space	10 pJ/bit/m^2
E_{tworay}	Energy amplification for two ray ground	0.013 pJ/bit/m^4
E_{elec}	Electric energy	50 nJ/bit
E_{DA}	Energy consumption for data aggregation	5 nJ/bit
q	Packet size	1024 bytes
X_{BS}	The X-axis coordinate of BS	49 m
Y_{BS}	The Y-axis coordinate of BS	175 m
C_1	Coefficient factors of energy	100/J
C_2	Coefficient factors of distance	5m
E_0	The initial energy of all nodes	2 J
M_1	The parentage of intermediate in N nodes	30%
M_2	The parentage of advanced in N nodes	20%
α	Initial energy factor of intermediate nodes	0.5
β	Initial energy factor of advanced nodes	2

Table 2 : The simulation scenarios involved various parameter values

VI. **Conclusion**

In this paper, we propose a novel Hybrid Optimization Approach for Energy-efficient Routing (HOAER) in Wireless Sensor Networks (WSNs). The main focus of HOAER is on optimizing energy consumption by extending the lifetime of the network through the use of both Ant Lion Optimization (ALO) and Genetic Algorithms (GA) for cluster formation, CH selection, and efficient routing of data to the base station (BS). It was demonstrated that our approach could improve network performance in homogeneous and heterogeneous network models with significant improvements over the best state-of-the-art protocols, including EE-TLT, STDC, LEACH-VA, and PEGCP. The proposed HOAER protocol achieves an excellent balance between energy dissipation and network longevity through the distribution of nodes into well-optimized clusters and selecting CHs based on energy levels and proximity to the BS. Efficient routing strategies are applied in the HOAER protocol by using Dijkstra's algorithm along with chain-based techniques for ensuring the data delivery to the BS with minimal energy consumption. The results of the simulation show that HOAER has an upper hand over the compared protocols regarding energy efficiency, ratio of living nodes, and time to first node dead, half nodes dead, and last node dead, with tremendous improvements in energy consumption and network lifetime. Although the current implementation focuses on static, homogeneous sensor nodes, future work will explore more dynamic and complex network scenarios.

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