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Optimizing Wireless Sensor Networks through Ant Colony-Based Localized Mesh Topology

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The growing need for faster and more effective data handling and data transfer capabilities of a network require energy-efficient and more powerful smart sensor devices. These devices have become increasingly necessary in wireless sensor networks (WSN). The architecture or topology of WSN can greatly impact the organizational efficacy and connectivity among the sensor nodes employed within the given area. It is foremost important to implement a robust network topology which must be capable of ensuring continuous and reliable communication within the whole network. This research paper presents an effective approach based on Ant colony scheme to optimize mesh network topology ant colony optimization (ACO) is used to place the sensor nodes optimally in the given area of the whole network. The proposed research carries out comprehensive performance evaluation of the network under various QoS parameters such as bandwidth, throughput, delay, residual energy and routing load. These parameters shows the effectiveness or adaptability of the network with different and dynamically changing communication requirements suggested by this topology scheme. The network based on the proposed method has been simulated several times and the achieved simulation patterns have been analyzed under the mentioned QoS constraints.
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WSNs comprise of large number of low-power devices called nodes which are dispersed over a huge area to collect and transmit data.[1–5] The pattern in which these nodes are connected is called a network in which these connected nodes can communicate with one another. This kind of network can be used for a number of purposes, including environmental monitoring, industrial automation, healthcare, and agriculture.[6] WSNs can be used, for environmental monitoring, WSN can be used by gathering information through sensor nodes to monitor weather patterns, water quality, and air quality. Whereas, in the healthcare industry WSNs can be used to track patients' vital signs and spot any anomalies.[7–9] WSNs can also be used in agriculture it can help to monitor various parameters which include soil moisture monitoring, temperature monitoring, and nutrient levels monitoring to maximize crop production[10] through mobile sensor nodes.

A wireless sensor network (WSN) is made up of numerous nodes with sensors and controllers that collect and track data as well as interactions with the surrounding environment. This facilitates the establishment of connectivity amongst people, computers, and the environment. Figure 1 shows the actual visualization of WSN topology in the given coverage area to be sensed where mobile sensor nodes are distributed and attached to one sink node. These sensor nodes establish the connection according to the algorithm so that data can be communicated from one node to another without any hindrance. The sink node is responsible to communicate the data accumulated through the sensor nodes to the end user for control, verification and management through the internet. The working efficiency of WSN greatly depends upon the algorithm used to establish connection between sensor node and optimizing the pattern for dynamically changing circumstances.

WSNs operate in multiple modes, which are enumerated below:

(a) Static Mode, where sensor nodes are busy keeping an eye on stationary objects like structures, roads, and bridges as well as the human body organs are considered in case of medical monitoring.[1,2]
(b) Dynamic monitoring, in which area monitoring is done (for example environmental monitoring and generating alerts for disaster management are involved).[7,9,10]
(c) Hybrid monitoring techniques, this involves area-entity monitoring, which is a combination of keeping an eye on both stationary objects and moving traffic.[10]

In WSNs, it is very much likely that the deployment of sensor nodes in a given network may vary greatly, from thousands to millions. These deployments can be performed in two ways (i) in an arbitrary manner or (ii) according to a pre-planned structure. In arbitrary structure, nodes are dispersed randomly, whereas they adhere to a preset configuration in a random deployment.[11] The communication of sensor nodes within a network is largely dependent on the WSN topology. Although there exist several types of topologies like bus, ring, tree etc but there are three typical WSN topologies:

1. **Star topology** (Fig. 2): In this a central base station serves as a channel for sensor communication in a star topology. As all nodes in this topology communicate data through a single point, this arrangement facilitates improved management.[6]
2. **Mesh topology** (Fig. 3): In this topology, sensor nodes can exchange data directly with one another. As each node in this topology can communicate with other nodes, a reliable and fault tolerant network is formed, allowing data to travel via different paths to get to its intended destination. This improved reliability and fault tolerance capability is achieved by this redundancy.[1–5]
3. **Tree topology** (Fig. 4): In this topology nodes are arranged in a hierarchical manner, giving the impression of a tree structure. Child node forwards the data to parent nodes until it reaches the root node, which is the top-level node. This makes an effective data routing made possible due to this configuration, and hence makes it appropriate for some special applications.

Furthermore, the choice of topology depends upon the specific needs of the WSN application, as each topology has its distinct advantages and trade-offs.[12–15] The efficacy of proper deployment and working of WSNs depends upon the proper understanding and implementation of various topologies, for optimizing fault tolerance capabilities, scalability, and energy efficiency.[11]

Each sensor node in WSN perform various measurements, then process these measurements accordingly and transmit it to a base station which may also be referred as sink node through a wireless channel. The base station is responsible to collect data from all the nodes, and processing of data is done to draw conclusions in given

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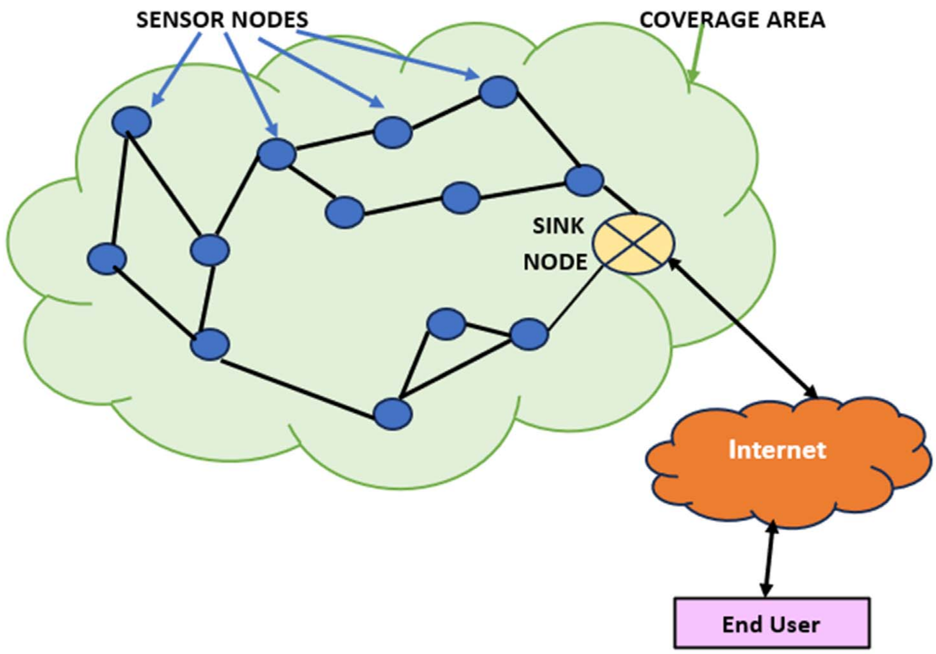


Figure 1. WSN topology.

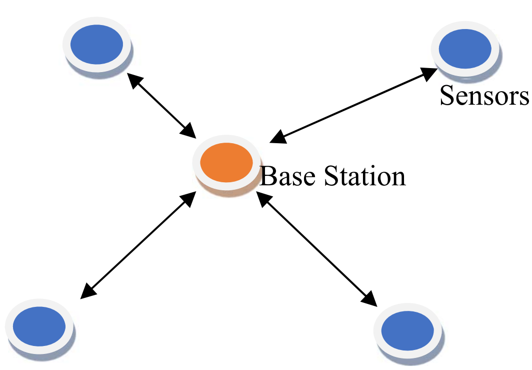


Figure 2. Star topology.

area of interest.[16] This data can directly be used by the user for further processing. These sink nodes are acting as the interface between the end user and the WSN.[17] There are number of constraints in WSNs for continuous data flow from sensor nodes to sink nodes, which may affect their reliability, scalability and efficacy. These constraints are important to consider and are listed below:

1. **Limited resources:** WSN comprises of small, low-power devices with restricted processing speed, storage capacity, and communication capability. This limited processing capability makes it difficult to complete complex operations like data processing and analysis through WSN.
2. **Energy efficiency:** WSNs are generally employed in the areas which are very difficult to reach and it becomes almost impossible to change the batteries or recharge the devices in those areas. Hence, energy efficiency is a crucial factor, and it is important to reduce energy consumption and increase network lifespan of the sensor node used in WSN.
3. **Scalability:** WSNs have large number of devices (from hundreds to thousands of devices) and continuously growing, it becomes difficult to maintain and operate the sensor nodes in such a huge network. This efficiently growing capability of WSN is a requirement for routing protocols and other network management strategies.
4. **Security:** WSNs are prone to security risks, such as eavesdropping, denial-of-service attacks, and tampering. Therefore, authentication, encryption, and intrusion detection procedures must also be included in WSNs.
5. **Interference:** WSNs operate in narrow radio frequency (RF) ranges, where interference from other wireless devices is likely possible. It is important minimize and control interference with other wireless devices so as to achieve good performance and reliability.
6. **Data management:** WSNs are responsible of producing huge data, which is challenging to organize and analyze. Data has to be efficiently collected, analyzed, and stored, and can be communicated over the network with minimum bandwidth and energy consumption.
7. **Fault tolerance and reliability:** WSNs are generally deployed in harsh environment and distant areas where repair and maintenance are difficult or impossible. WSNs must be self-organized so as to achieve fault tolerance and reliability. For continue operation even in the presence of node separation or failures, it must self-organized itself regularly. In case of total nodes failures, redundancy must be implemented into the network by associating some additional nodes to monitor the same environment. Since huge amount of data is to be collected or gathered, reliability is therefore a major design issue for WSNs. Routing protocols used in WSN must be highly reliable so as to manage interference, noise, and other environmental impairments that may occur during data transmission. Additionally, data synthesis and aggregation methods can also be used on collected data to enhance the its reliability and precision.

Challenges of the aforementioned areas, in WSNs, mentioned the difficulties to optimize network performance with maintaining mainly energy-efficiency and reliability. The node placement optimization remains one of the major issues in existing literature, as the placement of the sensor nodes determines vital network characteristics such as the coverage area, efficiency of communication, and energy consumption etc. The pervasive constraints and dynamism of

WSNs impose difficulty on solving the aforementioned issues by conventional optimization methods. Bio-inspired techniques address the abovementioned issues promisingly, for example, Ant Colony Optimization (ACO).

ACO is a popular metaheuristic algorithm that is inspired by the ant's seeking foraging behaviour. In ACO, artificial ants represent the agents desirous of discovering the optimal solution in the problem space. These artificial ants discover the potential paths of a solution and leave the pheromone trails to signal the path's attractivity and quality. At first, the paths are exposed to the random pheromone. The ant discovery of the paths becomes a function of the locally available information and the paths' globally obtained pheromone. Specific paths' pheromone amount is a factor that decides the choice of specific paths by ants. The stronger the pheromone on a certain path, the more likely it becomes that the path will be chosen by an ant. Moreover, an ant needs some criteria, such as the distance or cost, as the selected path during each step of its tour. A once created tour by an ant after constructing a solution, the pheromone trail is updated based on the quality of the solution found. Good solutions are reinforced by depositing more pheromone in the corresponding paths while poor solutions are weathered with a decrease in the pheromone in the corresponding path. This updating of the pheromone trail is important as it enables the algorithm to converge towards a solution area in subsequent iterations. ACO's strengths include its effectiveness in relatively difficult areas, adaptation to problem conditions, and the convergence to near optimal solutions. The ACO has been applied in various domains such as routing optimization, scheduling, vehicle routing and resource allocation, among others. The effectiveness of ACO in WSN lies in its ability to deal with dynamic factors of different environmental conditions and obtain near optimal solutions. In WSN, ACO follows the principles of swarm intelligence, considering it is where simple agents interact locally to collaboratively solve problems to dynamically control the network topology.

Need for the Topology Control for WSN

The careful consideration of selecting the geographical configuration of sensor nodes (network topology) is an important factor that needs to be taken care of Refs. 5–8. Hence, solutions for effective topology control are required in order to solve the inherent problems of reduced energy consumption, efficacy, and reliability within WSNs.

Resource utilization and communication outline is greatly influenced by three-dimensional arrangement of sensor nodes. Feeble topology management result in un-reliable networks with increased energy consumption and inefficient network performance. Therefore, efficient topology control mechanisms is important to build to meet dynamic node deployment requirements and resource limitations. Topology management must contain:

1. **Network connectivity:** Over wireless channels flexible topology control improves transmission quality.
2. **Coverage area:** Deployed topology should cover entire area after being configured.
3. **Resource optimization:** Use optimal WSN topologies so as to minimize resource consumption.
4. **Node failure management:** Transmission may be interrupted due to node failure, hence, self-managed topology must be employed.

To configure network topology following steps can be used

1. **Network setup:** This step involves the deployment of sensors with respect to coverage area.
2. **Topology configuration:** In this step, the topology is constructed using wireless links.
3. **Topology control:** There may be change in topology due to link failure or due to dead nodes, at this point there will be need for reconfiguring the current topology. This step can also be repeated if new sensors nodes are added into existing network.

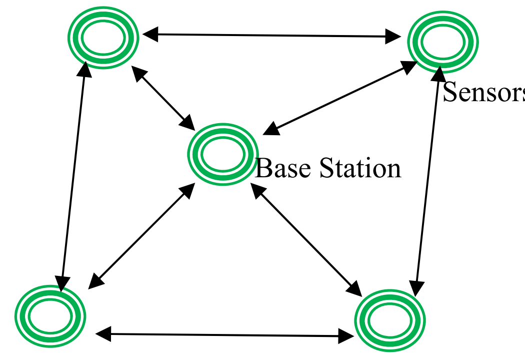


Figure 3. Mesh topology.

In this research work, Ant Colony Optimization method is investigated for localized mesh topology control for WSNs. The aim of the research is to improve service quality beyond conventional scalability and energy efficiency issues using the ant behavior of dynamically controlling the connectivity among each other. It particularly stresses on basis dynamic network topology control in localized mesh architectures.

Recent developments in WSN topology control section of the paper is dedicated to review the recent advances made in WSN. Ant Colony based Localized Topology Control for WSN section gives an overview of ant colony based localized mesh topology together with simulation set up and performance evaluation indicators. It aims at proving how well suggested strategy maintain balance trade-off between energy consumption, scalability, and flexibility in WSN by in-depth simulations and comparisons with conventional approaches used in mesh topology. Finally, conclusion of findings is presented in Conclusions section.

Recent Developments in WSN Topology Control

The researchers have put great efforts in trying to evaluate the possibilities and problems that encountered in WSNs using a mesh topology.[1,2] Some research papers have focused on suggesting combined ways of using distributed sensors for sensing in network topologies.[3] An efficient and dynamically optimizable topology control approach has also been designed for rechargeable sensor networks.[5] A few existing research works are available on improving energy efficiency in hierarchical topologies.[6] Researchers proposed an exceptional linkage evaluation technique which can be employed in an isolated node to link it up to another wireless sensor network topology. For example, a unique network design has been proposed where a WSN is constructed and a link assessment method is utilized to patch the isolated nodes.[7] However, for further advancement in this area, some researchers have concentrated on inferring network architecture without prior knowledge.[8] Dynamic topology control for reliable group communication over mobile ad hoc networks can be found in different literatures.[9]

The existing literature on topology control has shown that several topologies control algorithms exist for sensor networks which includes hierarchical, structural and topology-aware routing algorithms among others. But, none of these management approaches can efficiently handle both stationary and mobile WSNs as it necessitates better network topology management algorithms.[10] Therefore, in this paper a comprehensive review has been presented on some existing works that discuss numerous ways that researchers have put forward to improve topology control.

a. Under-water Sensor Topology Control: Some of the researchers have demonstrated that how the topology can be controlled

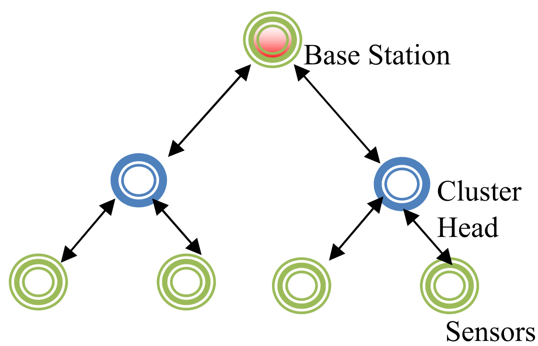


Figure 4. Tree topology.

when the sensors are put under water where their location continuously changing due water tides.[11]

b. Impact of Node Failure: Frequent failures of a node shorten the total lifespan of a network. In order to predict how long the entire network would last based on energy level, we can estimate the rate at which sensor's energy is depleted using mixed integer programming model.[12]
c. Networks of Distributed Sensors: There are several reasons why controlling topology for distributed sensor networks is very difficult. For instance, poor wireless links make it impossible to guarantee connectivity and also collecting data across large regions becomes a major problem. Uncertain updates in network topology can degrade network performance and increase control overheads as well. It is possible to use an objective function that maximizes energy consumption, and a genetic algorithm that manages the topology in distributed contexts.[13]
d. Mobile Sensor Networks: Network operations are challenging due to frequent changes in mobile sensor networks; where sensors may move at any time, coupled with additional difficulty brought about by cluster head selection procedures. These constraints may lead to low quality transmission. Game theory model can be implemented to determine the probability of a node being displaced in a mobile environment, as well as the amount of energy it has used.[14]
e. Hierarchical Topology: Hierarchical organization of topology for sensor networks could help to reduce energy consumption, latencies etc by placing sensors at different levels within a hierarchy with one cluster head being chosen per level. If there is any need for topology changes to take place from one level to another then this can be done without much control overhead.[5,6,15]
f. Domain Specific Networks: Sensor networks have many applications in diverse areas such as healthcare, military, maritime defense, surveillance and monitoring among many others. Although the network topology may shift from domain to domain, its stability is maintained through application of probabilistic algorithms.[16]
g. Spatial Correlation Management: It is important to note that spatial correlation is essential for maintaining dense network topologies whereas dynamic ones might negatively affect transmission quality of service (QoS). Sinks should use this approach by determining spatial-correlation factor through game theory algorithms in order to maximize resource utilization while regulating transmission power.[17]
h. Random Sensor Deployment: A questionable topological update can result from sensors distributed randomly over the network. The Markov chain approach ensures linearity in topology order, while Bernoulli binary distribution estimates these changes.[18]
i. Mesh-based Topology: A mesh-based topology can be modified to provide the most connectivity despite many reasons for degradation of a network's performance. An analytical model is able to approximate stationary nodes with wireless linkages. This however consumes more resources compared to other topologies like star & bus topology that vary in detecting range and transmission.[2]
j. Highly Mobile Environments: In such scenarios as complex topology development and administration due to highly mobile environments, there is excessive control overhead, energy consumption, and packet retransmission leading to lower performance of networks in general. Graph theory is one way software-defined networks could be connected to sensor networks so as to adapt quickly in frequent changing topologies.[19]
k. Flooding vs Hierarchical Routing: It uses up more network resources when compared to hierarchical routing across sensor networks flood based topology control method. It can optimize the use of grid based topology though. Creating a grid that enables linear ordering of sensors makes it easy to tell if there are active or inactive sensors, and monitor whether they are dead or alive across the network which allows constant topology changes.[20]
l. Zigbee Standard: Zigbee standard is designed for large-scale sensor networks. It provides long range communication at lowest power consumption but its hardware costs more than other networks.[21]
m. Mobile Sinks in Large Scale Networks: The use of mobile sinks in gathering coverage area and topology information for large scale networks optimizes energy consumption through reconfiguring topologies. However, within a highly mobile context, frequent shifts of mobile sinks can lead to packet collisions across the network as well as additional control overhead during reforming topologies.[22]
n. Hypercube Network-based Topology: Hypercube networks based on this structure assure reliable transmission over sensor networks. It employs the concept of "network on chips" that has little transmission power and bandwidth capabilities necessary for controlling topology choices. While research indicates that longer lifetimes are experienced by it compared to traditional network, it is also very efficient with respect to energy use.[23] A few literatures also exist on topology optimization and control using ant colony algorithm.[24]
o. Q-learning Method: Using Q-learning technique grants higher degree of control on sensor network topology. This way helps to build links by considering variables such as latency, intermediate nodes' residual energies and link quality.[25] Then the data gets sent to the sink node through some cut-vertex node. As opposed to depth-based routing or lifetime-aware routing (for example), it excels in energy consumption and optimal delay among other areas.
p. Topology Evaluation Model: In order to avoid packet loss over networks with respect to network dynamics constraints a model for topology evaluation was also created by researchers. For instance, numerous clusters are used so as to form a topology that can resist faults in highly mobile environments such as MANETs.[26] It's findings from simulation-based studies have best energy consumption, latency among others.
q. Topology-aware Routing: In order to maximize utilization of resources, routing protocols are designed in such a way to adapt themselves to changes in network topology. Numerous factors must be taken into account, including the coverage area, available bandwidth, connection quality, and the distance between intermediatory nodes. Existing research shows that, in comparison to current routing systems, topology-aware routing can be used to optimize resource utilization.[27]
r. Spanning Tree-based Topology Control: Compared to exiting topology control algorithms, spanning tree-based topology control mechanism provides a more flexible and fault-tolerant network. To ensure maximum connectivity, it dynamically design the topology based on the covered area of consideration. The spanning tree is modified to respond to all the changes in topology in the event of a node failures. When compared to present topology and their control strategies, spanning tree topology performs better in terms of energy consumption.[28] For

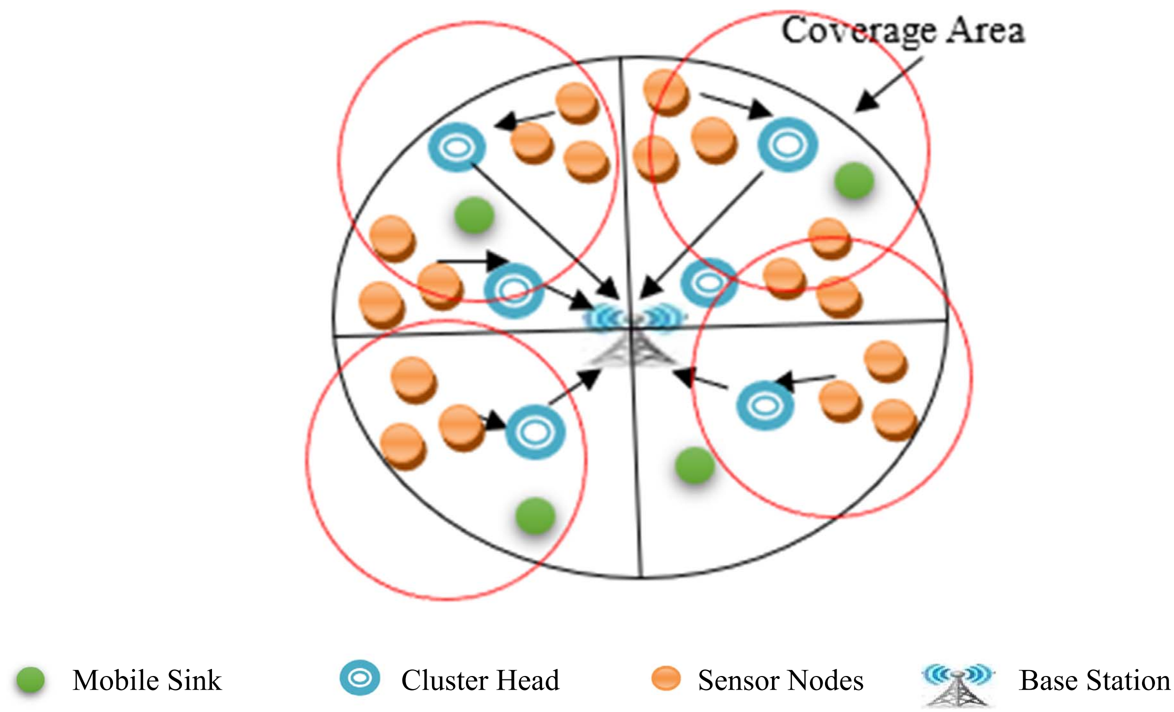


Figure 5. Ant Colony based local mesh topology formation.

Table I. Throughput comparison of MT-ACL and MT schemes.

	Simulation scenarios		
Sensor density	MT	ACL-MT	Percentage improvement of throughput of ACL-MT over MT
50	199.92 Kbps	235.62 Kbps	17.85714286
100	373.66 Kbps	468.86 Kbps	25.47770701
150	535.5 Kbps	703.29 Kbps	31.33333333
200	671.16 Kbps	931.77 Kbps	38.82978723

ultra-reliable communication, spanning trees can also be employed to create a spatial network topology.[29] In comparison to previous spanning tree-based systems, it is more efficient and makes use of graphs to store topology control information over the entire network.[30]

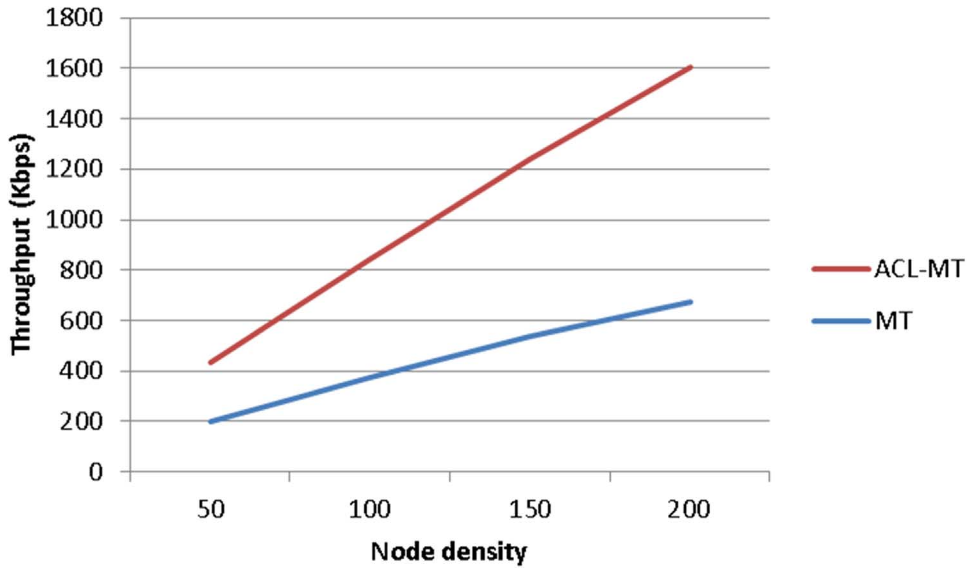
Even though large amount of research has been done on WSNs; some research gaps still exist, This is so because the previous research has heavily concentrated on static settings while ignoring the changing nature of WSNs, especially in environments with high mobility where nodes move quite a lot. One way to close these gaps is therefore to propose a localized mesh topology that is enhanced by ACO. The literature does not provide comprehensive studies on energy-efficient techniques for mesh-based networks; this proposed undertaking fills this gap by utilizing the bio-inspired and adaptive features of ACO.

This research seeks to address these issues by focusing strongly on usability, scalability, and reliability in dynamic WSN deployments. Further, it is required to carefully investigate the quality of service (QoS) implications by using ACO for optimization localized mesh topologies for control management. The proposed investigations undergone in this manuscript intends to provide insights into ensuring the sustainability of the network, reliability, bandwidth utilization, and other aspects under these given circumstances. The proposed study aims to provide solution to fill-up these research gaps and improve the available knowledge and use of localized mesh topologies in WSN by creatively using ant colony algorithms for optimization.

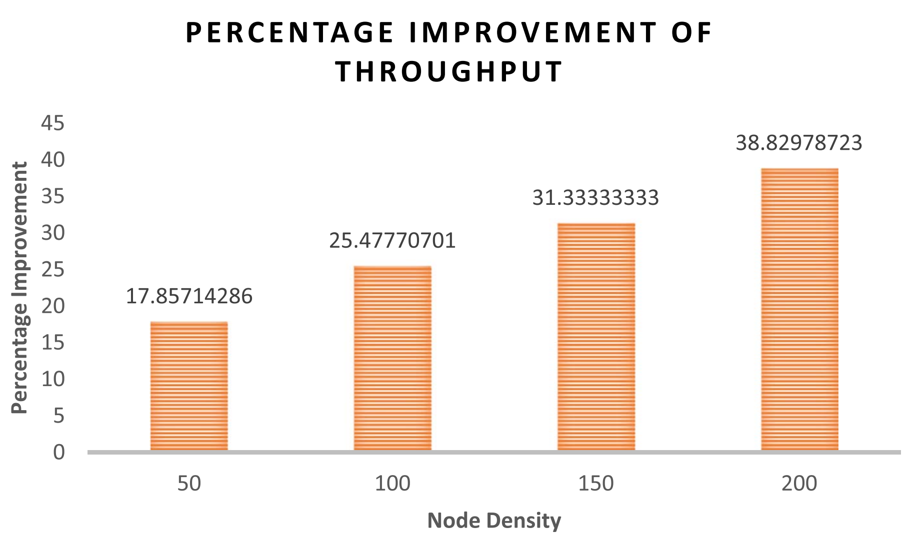
Ant Colony based Localized Topology Control for WSN

In the framework of WSNs, a number of optimization strategies have been investigated; each has advantages and special qualities of its own. While Particle Swarm Optimization (PSO) uses the collective behavior of fish and birds as inspiration to repeatedly improve solutions, Genetic Algorithms (GA) use evolutionary concepts to evolve solutions, and Simulated Annealing (SA) investigates the systematic solution to imitates the annealing process in metallurgy.

ACO is preferred over alternative strategies due to its unique benefits specifically designed for WSNs. It is ideally suited for situations where sensor nodes may function in extremely mobile or unexpected conditions since it performs effectively in dynamic and decentralized contexts. Its decentralized structure and flexibility in responding to shifting network topologies fit very well with WSN features. In addition, ACO provides a balance between exploration and exploitation and is resilient to local optima. Compared to Particle Swarm Optimization, Genetic Algorithms, and Simulated Annealing, ACO's distributed architecture complements WSNs' naturally decentralized design. At the sensor node level, this feature guarantees effective and independent decision-making, lowering the need for centralized control and cutting down on communication overhead.



(a)



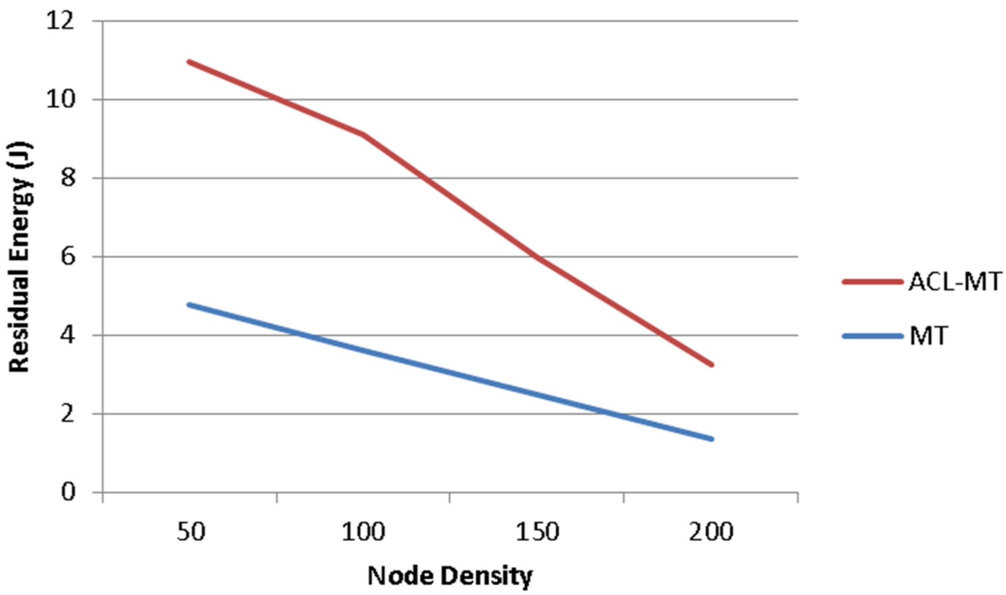
(b)

Figure 6. (a) Throughput plots and (b) Percentage improvement of ACL-MT over MT in terms of throughput.

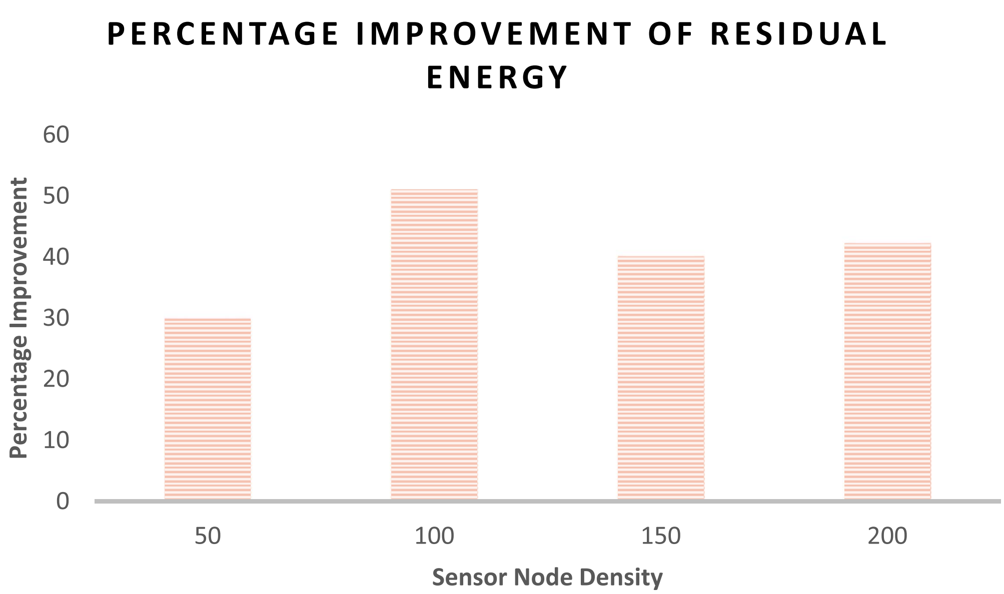
Table II. Residual energy comparison of MT-ACL and MT schemes.

	Simulation scenarios		
Sensor density	MT	ACL-MT	Percentage improvement of residual energy of ACL-MT over MT
50	4.7719 J	6.19752 J	29.87531172
100	3.631404 J	5.48471 J	51.03552235
150	2.490908 J	3.488842 J	40.06306134
200	1.350412 J	1.92066 J	42.22770532

There is a huge application area of optimizing WSNs through Ant Colony-based Localized Mesh Topology which cuts across multiple industrial and academic domains by providing highly adaptable solutions to seemingly impossible problems.[2,19–24] Industrial problems that have to do with real-time monitoring, environmental data collection for the monitoring of climates and the detection of pollutants for disaster recovery are rendered solvable.[21–23,31,32] As far as precision agriculture is concerned, the solution enables optimal precision irrigation, crop monitoring and soil monitoring for multi-faceted solutions. In addition, industrial applications such as asset tracking for predictive programmed maintenance and process optimization to reduce downtimes. In the academic field, the systems can be used to improve wireless communication through network optimization and bio-inspired system design.[5–10,31,32] As per the motivations mentioned above, the investigations in this paper will add to the academic spectrum on network scalability, energy conservation, and versatility. It is because it promotes other areas such as computer science, electrical engineering, and telecommunications to explore new ways for developing new applications that inspire innovation. Equally, the findings will motivate future studies on emerging applications for ACO and localized mesh architecture in various sectors like smart cities, health systems, IoT



(a)



(b)

Figure 7. (a) Residual Energy plot and (b) Percentage improvement of ACL-MT over MT in terms of Residual Energy.

networks aiming to enhance and promote development in wireless sensor technologies

Proposed scheme.—To improve the network performance, the suggested method based on Ant Colony-based Localized Mesh Topology Control for WSNs has been developed in phases. During the setup phase, signal is dispersed locally by the sensor nodes which establishes the basis of decentralized decision-making. The adjustment of the connectivity of these sensor nodes has been done throughout the examination phase in response to variations in signal concentrations which allows further self-organization which taking external provocations in account. In the assessment stage evaluation of the the effectiveness of the modified topology has been performed, while continuously updating the nodes with their signal connections to fine-tune these connections. Because each phase is separate in itself, global communication is not required, which improves energy efficiency in WSNs with limited resources. This step-by-step method ensures a reliable and self-organizing topology which can be customized to the changing demands of WSN topologies by using the inborn compliance of ant-colony based algorithms. The discussed phases of the proposed scheme are described in detail further as:

Sensor deployment phase.—In the first step, which is the sensor deployment phase, the whole coverage area of the network is divided into local blocks of size 1/n. Then after, all the sensors are dispersed in each of these blocks arranged accordingly as shown in the Fig. 5.

Topology formation phase.—The second phase is the network topology development phase which is very vital. In this stage, the sensors which are dispersed in the network and communications status achieved between them drive the network to be dynamically self-organized. As connecting links has been established between sensor nodes, the network structure took its shape with achieved optimized connectivity and adaptability. This process is known as topology formation or development. This stage plays an important role in establishing the outline for the WSNs, which ensures an effective and adaptable arrangement of the network which can meet the customized requirements of the surrounding environment and circumstances. There are various processes through which topology formation or development has been established which are discussed as follow:

Step 1: Move the mobile sinks to the local blocks.

Step 2: Deploy the sensors in such way that each sensor must be in the range of mobile sinks.

Step 3: Mobile sinks are responsible to select the node as cluster head (CH) having minimum distance with mobile sinks and it should have highest residual energy also.

Step 4: Set its signal value (Ph) = HIGH and broadcast this message over local block only, to intermediate sensors. Ph value will be decreased w.r.t. energy consumption and in case, if current cluster head has minimum Ph value as compared to neighbors, cluster head selection process is initiated by mobile sink only.

Step 5: Inside a local block, JOIN request is forwarded by CH to the intermediate nodes. A node can accept the JOIN request to join the local mesh. This step is repeated till the complete formation of a local mesh. This step is repeated w.r.t. each local block.

Step 6: After the mesh formation at local level, each sensor can forward the data to each other and finally, aggregation is performed by cluster head only and it is forwarded to the base station.

Topology maintenance phase.—Topology Maintenance is an imperative step which must be considered with great priority in establishing the reliable topology and hence, it is considered very important in the proposed method. In this stage maintaining and enhancing the network structure is to be focused upon for a specified amount of time once the original topology has been set. In order to deal with dynamically changing state of dispersed sensor nodes in critical situations or unexpected events, it needs constant monitoring, adaptation, and self-organizing processes so as to ensure that the network always maintains its effectiveness, connectedness, and sensitivity during its operation. Continuous up-dation in maintenance and organization process for topology is due to several problem, these are:

- **Intermediate node failure:** In case of node failure, mobile sink may be used to replace the dead node. But in case of multiple node failure, mobile sink must be placed that it should be in range of other nodes.
- **Cluster head failure:** In this case, mobile sink immediate finds the nodes with highest residual energy in the local region, and it randomly elects an optimal node as Cluster head.

Simulation and results.—A popular discrete-event simulator Network Simulator version 3 (NS-3) has been used for simulation purposes and to generate the output for the proposed WSN topology. This is a networking research simulator which runs on the Linux platform. The NS-3, provides a powerful platform for simulating WSNs. NS-3 is capable of modeling a wide variety of communication protocols and network topologies and can be extended to perform simulations to meet specific research requirements. For example, it allows to investigate a number of network performance metrics in greater depth, such as throughput, delay, and packet loss. The limitations of NS-3 is that it can be difficult to configure and difficult to interpret the results. Furthermore, the NS-3 simulations can be computational costly, especially when scaled up to larger networks or longer durations. Both Wireshark and NS-3 simulation tools compliments each other by providing real-world validation and verification of simulated network behavior.

The proposed Localized Mesh Topology Control for WSN based on Ant Colony algorithm has effectively been simulated and the results have been generated using this NS-3 simulator. The total dispersed nodes density was dynamically changed from 50 to 200 nodes. The node density was systematically changed so as analyze the capacity of network topology to handled various network for different network scales.

One of the most important and vital aspect of simulation was the number of mobile sinks or base stations, which was set equal to the number of local blocks in the coverage region i.e. 1/n. Furthermore, the initial energy of each sensor node was set at 30 J, and the rates of transmission and reception between the sensor nodes were set to 10 units. The network coverage area was set at 4000×4000 units for the required simulation. The simulation interval was set at 600 s so as to fully cover the dynamic nature of the WSN Topology during simulation and ensuring the reliable results.

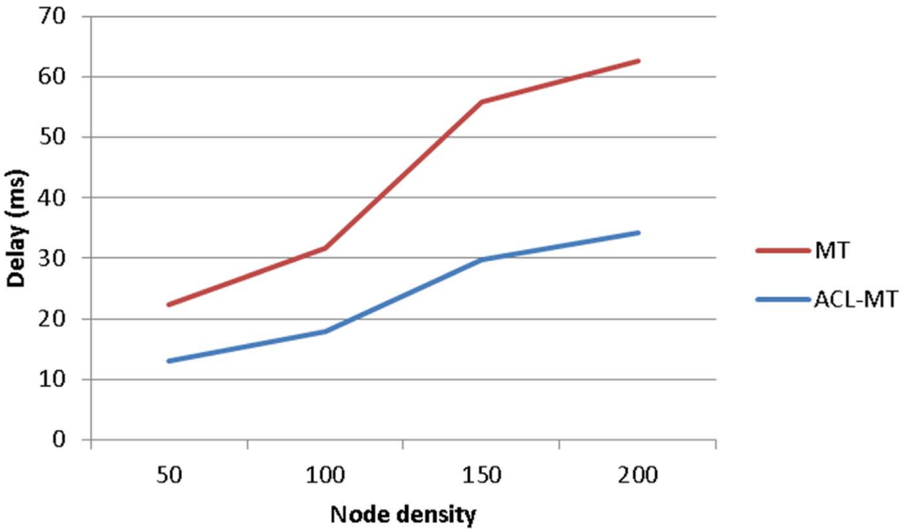
The parameters for ACO algorithm to be used in WSN are carefully chosen. The number of mobile sink nodes (1/n equal to the number of local blocks) impacts the data collection and routing efficiency. Furthermore, setting initial energy of sensor nodes at 30 J and transmission and reception rates at 10 units ensures uniform energy utilization and prevents early energy depletion in some specific nodes, improving sensor node lifespan. These parameters are determined through detail experimentation, where changing node densities and network scales have been examined to analyze robustness and scalability of the ACO algorithm.

Further, using Wireshark, PCAP (Packet Capture) trace files has been created during the simulation which were then analyzed. A thorough investigation and analysis has been done on the packet conversations patterns, established connections, and general network behavior under the effect of the suggested Ant Colony based Localized Mesh Topology Control. The effectiveness of the method produced has been validated by comparing the results achieved with the simple mesh topology outcomes in the following writeup.

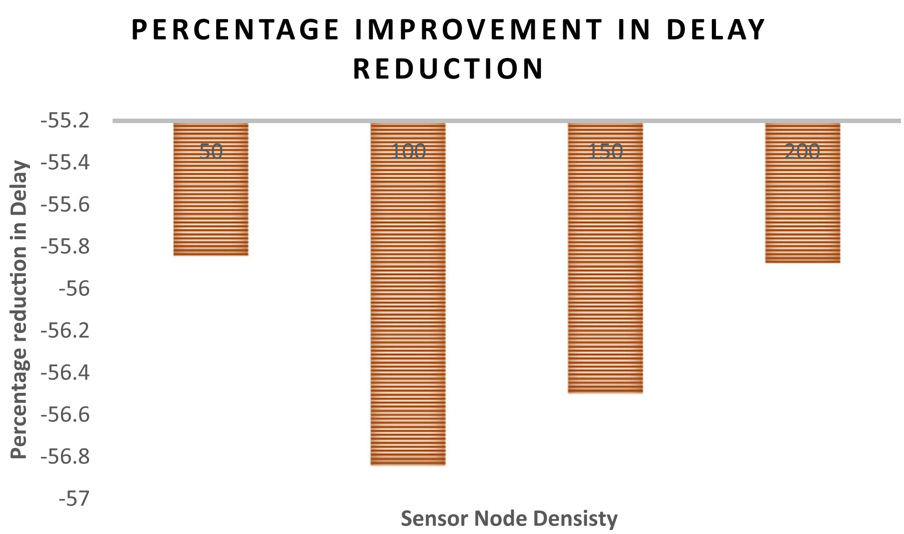
Throughput of a network topology is referred as the speed with which data is successfully transferred from node to the sink in the given network. The throughput is always been a crucial parameter in the assessment of network performance, and the simulation results are visually shown in the Fig. 6a. The comparative performance and their difference of the suggested **Ant Colony Optimization based Localized Mesh Topology Control (ACL-MT)** against traditional **Mesh Topology (MT)** configurations is clearly depicted in figure. Figure 6b illustrates the improved percentage of throughput achieved by ACL-MT over MT algorithm. The graph shows significant improvements of approximately 17.86% to 38.83% in throughput, showcasing the efficacy of ACL-MT in optimizing network performance over MT.

In the Table I, the throughput results of both networks under study are shown. This tabular representation of these quantitative values made it possible to compare the two methods in detail. In both network topologies, the throughput values gradually increase with increased sensor density. But out of the two methods the ACL-MT system exhibits the highest throughput and continuously outperforming the MT scheme. This investigation highlights the improved data transmission rates that has been achieved with the Ant Colony optimized localized mesh topology, especially when the sensor density grows.

The residual energy of the network is defined as the total energy level that has left in the employed network sensors which directly affect the lifespan and performance of the whole network. Hence it an important parameter to measure as it suggests the network capability to withstand with limited energy resources. The residual energy variations within the WSN topology for both the networks under study has been shown in the Fig. 7a. Understanding on how various sensor densities of nodes can impact the remaining energy in Mesh Topology (MT) and Ant Colony based Localized Mesh Topology (ACL-MT) schemes can be attained by looking at the trend shown in Fig. 7a. The residual energy between the MT and ACL-MT methods is compared quantitatively in Table II for a range



(a)



(b)

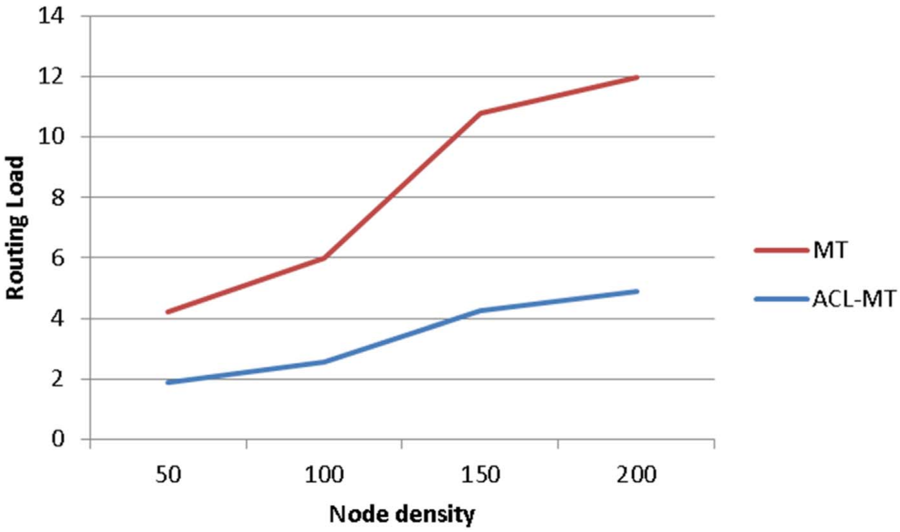
Figure 8. (a) Delay plots and (b) Percentage reduction in achieved delay in ACL-MT over MT Scheme.

Table III. Delay comparison of MT-ACL and MT schemes.

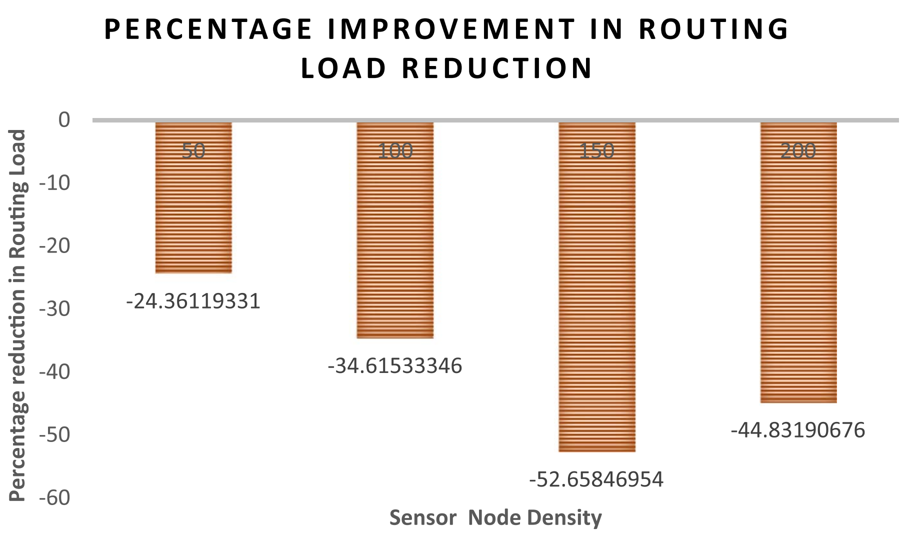
Sensor density	Simulation scenarios MT	ACT-MT	Percentage improvement in reducing delay of ACL-MT over MT
50	21.1281 ms	9.329329 ms	−55.84397556
100	31.8955 ms	13.76577 ms	−56.84102773
150	59.8429 ms	26.03303 ms	−56.49771318
200	64.2581 ms	28.35235 ms	−55.87739133

of sensor density from 50–200. The values in the table determine how residual energy tends to decrease as sensor density rises from 50 to 200 sensors. Interestingly, at the maximum sensor density, both designs show the lowest residual energy levels, but still ACL-MT out performs MT throughout with different node densities ranging from 50 nodes to 200 nodes. Figure 7b depicts the improved percentage in residual energy accomplished by ACL-MT over MT. the enhancement ranges from approximately 29.88% to 51.04%, through which ACL-MT shows its effectiveness in optimizing energy utilization, representing its potential for long-lasting network lifetime and enhanced sustainability.

Another key performance indicator is the delay, which can be defines as the time taken for data to travel across a network or for conversation to occur. The Fig. 8a illustrates the behavior of total delay occurred in both network topologies along a wide range of sensor density in a WSN. The latency or delay characteristics of the MT and ACL-MT methods under various sensor density are compared quantitatively in this Table III. From 50 to 200 sensors, there is an increasing trend in delay factor, as shown by the values in the Table III. Notably, at the highest sensor density, both methods display their maximum delay levels. In contrast to the MT scheme, ACL-MT exhibits more effective delay control, maintaining at their optimum levels. In WSN, it is essential to comprehend these delays in order to maximize responsiveness and communication efficiency. Figure 8b represents the reduction percentage of delay achieved by ACL-MT as compared to MT, which shows the significant reduction ranging from approx.%−55.84% to −56.84%. This enhances the performance ability of ACL-MT in justifying delays, to make ACL-MT real-time more sensitive to input data and efficient to provide output with minimum delay.



(a)



(b)

Figure 9. (a) Routing Load and (b) Percentage reduction in Routing Load of ACL-MT over MT scheme.

One more important parameter used to judge the performance of the WSN topologies is routing load characteristic. To optimizing network traffic and to ensure effective data transfer, a good understanding of route load dynamics in WSN is very much required. To get deep insight of the performance of proposed algorithm both MT and ACL-MT are analyzed on the basis of their respective routing load characteristics w.r.t. various node densities. Figure 9a illustrates how different sensor densities affect the routing load in the ACL-MT and MT schemes. The routing load characteristics of the MT and ACL-MT schemes under various sensor density are compared quantitatively in Table IV. For both methods, the data in the table show a steady increase in routing load w.r.t. to sensor density. For the MT method, the routing load reaches its highest value at the maximum sensor density of 500. Whereas, in ACL-MT scheme the routing load is significantly lower than that of the MT scheme and stays nearly constant. The table highlights the advantages of the suggested ACL-MT scheme over the conventional MT method, especially in situations with high sensor density, and offers quantitative insights into how proposed ACL-MT scheme is effectively managing the routing loads. The Fig. 9b shows the percentage improvement in reducing routing load in ACL-MT scheme over MT scheme, which shows considerable enhancements ranging from −24.36% to −52.66% approximately. This showcases the effectiveness of ACL-MT in reducing routing overhead which leads to more efficient network resource utilization and improved overall performance.

Variations in packet transmission using network topology schemes enables more adaptive, efficient, and reliable network communication in ever changing and dynamic environments. Figure 10 illustrates the dynamic changes in packet transmission during the total time taken for simulation in MT scheme. According to the results shown, the MT scheme represents a great deal of inconsistency and randomness in data packet transmission. This random behavior of the scheme can be well understood by considering the parameters such as sensor shifting activity, variable network conditions, or dynamic topology modifications. It is important to understand these changes so as to realize the stability and reliable performance of the MT scheme with regard to packet delivery in the WSN topology system. Additionally, the different patterns or trends in packet transmission dynamics might produce an important insight for network protocol improvement and network optimization or management.

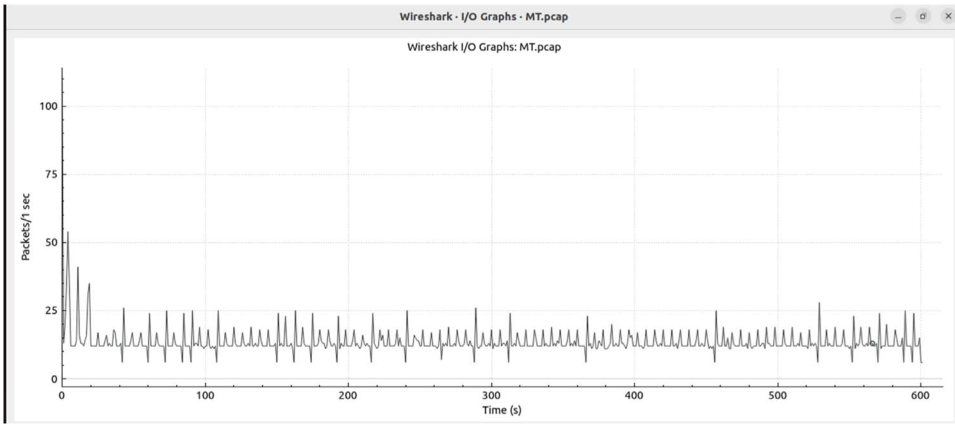


Figure 10. Variations in packet transmission using MT scheme.

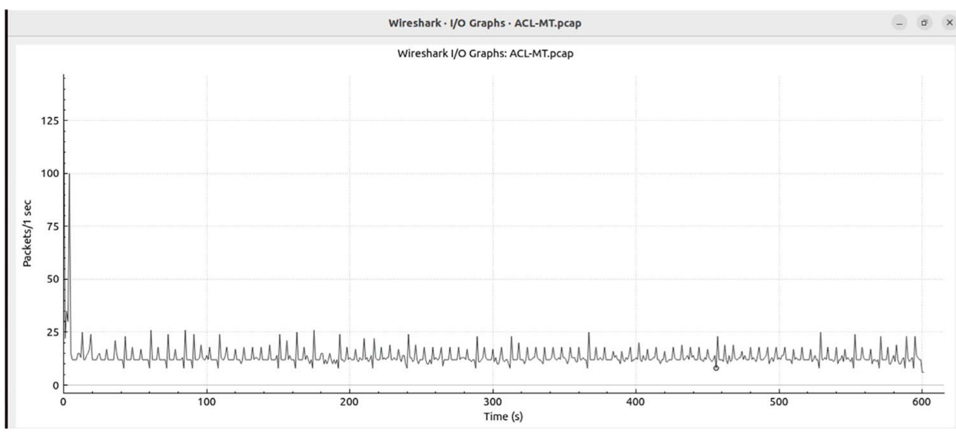


Figure 11. Variations in packet transmission using ACL-MT scheme.

Table IV. Routing load comparison of MT-ACL and MT schemes.

	Simulation scenarios		
Sensor density	ACL-MT	MT	Percentage improvement in reducing routing load of ACL-MT over MT
50	1.87545	2.332332	−24.36119331
100	2.5565	3.441441	−34.61533346
150	4.26328	6.508258	−52.65846954
200	4.89401	7.088088	−44.83190676

The changing patterns or trends of packet transmission for the proposed Ant Colony-based Localized Mesh Topology (ACL-MT) scheme over a given time of the simulation are represented and shown in Fig. 11. As depicted in the figure ACL-MT scheme shows the peaks and valleys in the packet transmission behavior over a particular course of. Additionally, ACL-MT scheme also shows a lot of randomness in its packet transmission for the given time of simulation. The differences recorded in the transmission pattern of ACL-MT scheme may result from real-time modifications made by the ACO method used, modifications done to the network environment, or dynamic changes to the localized mesh topology. These differences must have to be understood for stability and better network performance of ACL-MT scheme with regard to packet delivery in WSN as well. Transmission patterns or trends in the packet transmission dynamics of the ACL-MT scheme also offers useful information for improving the network performance. The difference between both schemes is clearly visible from the given Figs. 10 and 11. ACL-MT shows higher packet transmission rate per second than that of the MT scheme and hence the proposed scheme utilizing bio inspired ant colony method of optimization performs better than existing mesh topology scheme.

Also, improved throughput, increased energy economy, decreased latency, and better routing load management make the Ant Colony-optimized ACL-MT scheme a viable option for enhancing wireless sensor network performance and dependability. The results highlight the potential of ACO and localized mesh architecture in resolving important issues and improving wireless sensor network performance overall.

Conclusions

The investigations in this paper have proposed a new method of dividing a existing mesh topology of size “n” into small chunks of localized topology of size “1/n” and optimized its performance using bio-inspired technique known as ant colony method. This proposed topology has been analyzed for different sensor densities ranging from 50–200 sensors. The performance of the ACL-MT scheme has been evaluated under various QoS constraints such as throughput, residual energy, delay, routing load and packet transmission time etc. The underwent network analysis of the proposed scheme w.r.t. the existing mesh topology scheme shows that, in comparison to the ACL-MT scheme, typical mesh topology based WSN has not been able to maintain network performance in terms of the aforementioned QoS metrics. Both the MT and ACL-MT methods produced the minimum throughput for lowest sensor density say 50 sensors only. It can also be concluded that the throughput has been increasing with increased sensor density and it is maximum at maximum sensor density say 200 sensors for both ACL-MT and MT. Residual energy also shows the same trends for both network schemes and changes in relation to sensor density. But, in comparison to ACL-MT, the MT scheme has the minimum residual energy and the extreme sensor density. The delay factor also varies in relation to sensor density as well. In comparison to MT system, ACL-MT optimizes its network topology well under the limitations of dynamically changing various sensor densities. Moreover, ACL-MT provided the minimum amount of routing load as compared to the MT scheme, where its performance suffered because of the highest amount of routing burden.

In summary, the findings in this paper explored various sensor topologies and investigated the existing mesh- topology in detail and presented a new method of dividing the mesh topology in Localized Mesh Topology (ACL-MT) based on Ant Colonies. Further, the study undergone has presented the superiority of the ACL-MT scheme over conventional Mesh Topology (MT) in WSNs through a thorough various performance analysis done on Quality of Service (QoS) constraints, such as Throughput, Residual Energy, Delay, and Routing Load, for various sensor densities from 50–200 sensors. For future investigations directions, broaden area of examination of ACL-MT performance to encompass other network categories, like Vehicle Ad Hoc Networks and Mobile Ad Hoc Networks can be suggested for researchers to pursue. The investigation can be proved for innovative integration with IoT and edge computing, while the adaptation of ACL-MT to emerging communication standards can also be researched. Thus, the applicability of ACL-MT to different network domains has the potential to contribute to its applicability in actual applications.

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