

Metaheuristic based Data Management in IoT-Wireless Sensor Networks

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Abstract

The integration of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) has produced smart connected systems capable of collecting a large number of data and then making decisions based on that data. These systems encounter unique challenges such as limited power, excessive redundant data, and inefficient routing protocols. This review work provides solutions to these problems by employing metaheuristic-based algorithms that could better manage data in IoT-WSNs, focusing mainly on data fusion and reduction methods, finding the best route selection, and energy conservation. This study will also compare the most common metaheuristic-based algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Firefly Algorithm (FA) and it will discuss the different constraints which they may encounter.

Keywords: Internet of Things (IoT), Wireless Sensor Networks (WSN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Firefly Algorithm (FA).

1. Introduction

IoT-Wireless Sensor Networks combine sensor nodes and IoT platforms to sense, analyze, and manage environments. They have an impact on smart agriculture industrial monitoring, healthcare, and environmental sensing. Metaheuristic algorithms can solve NP-hard problems in WSN data management. These algorithms adapt and optimize processes in dynamic environments with limited resources. Figure 1 shows the integrated form of IoT with Wireless Sensor Networks.

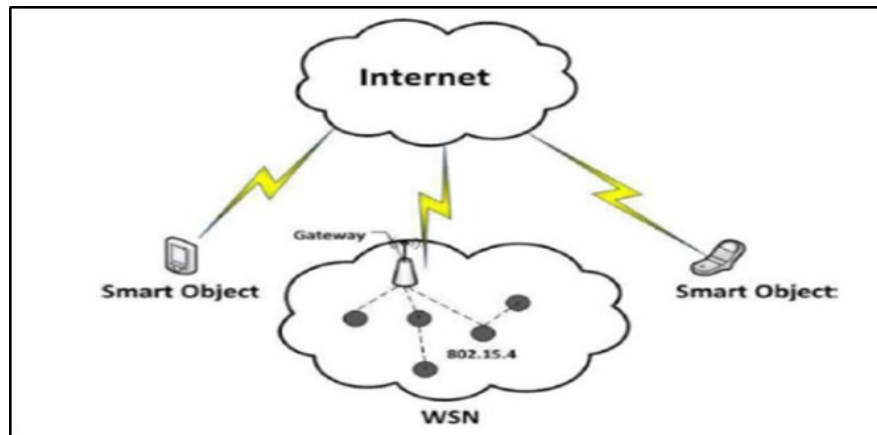


Figure 1. IoT-WSN Integration [16]

Metaheuristics-based data management in IoT-Wireless Sensor Networks (IoT-WSNs) helps to overcome resource limits by changing network structures, and large-scale deployments. IoT-WSNs create large amounts of data that need aggregation, routing, and storage while using less energy and time. Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization gives strong flexible ways to improve data handling. These common methods work to solve complex optimization problems with multiple goals. They produce good results without using too much computing power. Figure 2 illustrates the different metaheuristic algorithms.

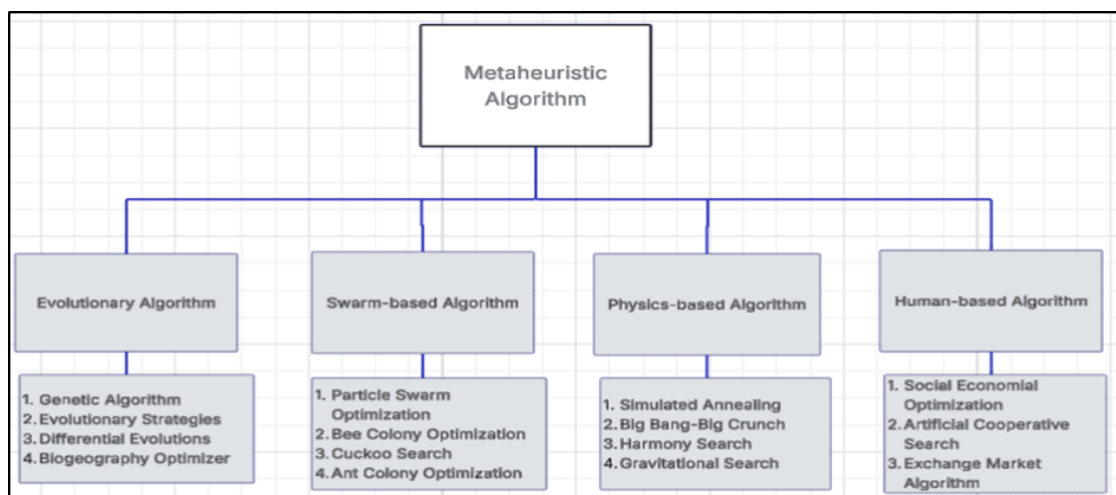


Figure 2. Different Metaheuristic Algorithms

Data management in IoT-WSN uses metaheuristic algorithms. These algorithms help to handle and oversee the data analyzed for comparison. The most effective algorithm will manage the process. Section 2 provides a general overview of previous papers to help

understand the topic. Section 3 explains the architecture diagram for IoT-WSN. Section 4 describes some metaheuristic algorithms. Section 5 discusses database management strategies based on metaheuristics. Section 6 presents a general comparative analysis of the algorithms.

2. Related Work

This study reviews previous works to illustrate that metaheuristic algorithms address the main IoT-WSN issues of energy utilization, secure routing, quality of service, and data management. To create smarter and adaptive routing techniques, different researchers have focused on combining metaheuristics with machine learning, blockchain, and reinforcement learning. The methods and objectives examined in previous research are shown in Table 1.

The Secure Energy-Aware Metaheuristic Routing [SEAMHR] method was developed to facilitate sustainable IoT-WSNs. This approach improves privacy and endurance by combining metaheuristic selection with energy-efficient routing. To conserve energy, it integrates multi-hop interaction with dynamic clustering. Furthermore, it reduces time delays and enhances performance based on node densities. In this work [2], an MHSEER framework was designed to improve energy consumption and security in industrial Internet of Things configurations. This was achieved by combining Ant Colony Optimization and Genetic Algorithms in a hybrid metaheuristic model. This research examines maintaining a balance between low energy consumption and reliable security, illustrating that route optimization can help minimize packet loss and enhance the lifespan of sensor nodes.

The introduction of blockchain technology to route planning and fraud detection is the focus of this work [3]. Combined with metaheuristic techniques, it developed a system that is highly resistant to distraction and fraudulent information detection. This is crucial for continuous monitoring in military or commercial networks where hazards are frequent. IoT, WSNs, and Sensor Cloud (SC) environments share numerous characteristics; however, they also approach data collection in specific ways, as explained in this work [4]. This study highlights that energy, bandwidth, and latency considerations require smart routing techniques, such as metaheuristic-based algorithms, to provide accurate and quick data transmission.

According to this research [5], WSNs are important sources of large data in IoT systems. This highlights the importance of using scalable and adaptable methods for effectively

managing data transfer and processing. In order to achieve this, metaheuristic technology will be used to enhance the transmission of data. IoT-WSN fusion and analysis techniques have been reviewed in this research [6]. This approach demonstrates the importance of adaptable real-time algorithms for handling shifting sensor input. Additionally, it discusses how metaheuristic models work with sensor network-based multipurpose problem solving. This work [7] proposed a routing method that prioritizes energy efficiency solve QoS problems. This approach mainly evaluated throughput, latency, and dependability. Metaheuristic techniques will be implemented to enhance these parameters. This work [8] investigated the role that WSNs perform in disaster management. For important operations, they prioritized smart energy routing and adaptive data exchange. Based on this study, metaheuristic optimization offers rapid responses along with improved application of resources in emergency situations.

A hybrid metaheuristic methodology for finding cloud-edge computing solutions with QoS monitoring was explained in this research work [9]. In this article, offloading tasks will be managed through the combination of genetic algorithms with particle swarm optimization. Task management in data-load IoT wireless sensor networks can be efficiently performed with this method. This work focused on swarm-based and evolutionary management for task offloading [10]. The goal of this technique is to improve the WSNs' battery life. It was demonstrated that the use of metaheuristics for altering task scheduling impacts the networks' lifespan and performance in many conditions.

Aslam and colleagues (2024) [11] proposed a smart setup to optimize wireless charging paths to reach critical nodes in renewable sensor networks. It mainly focused on deep learning and optimization methods to manage energy availability and task importance. This method works to support environmentally friendly IoT systems. Bozorgi and collaborators (2021) [12] showed that the Whale Optimization Algorithm (WOA) helps group IoT-WSNs into clusters. It achieves faster convergence and uses fewer computational resources when compared against older clustering methods. The results of this method were achieved by selecting adaptive cluster heads using swarm intelligence. Mahato et al. (2024) [13] used a combined method of machine learning and metaheuristic optimization to detect harmful actions in IoT and IoMT networks. This approach gives high accuracy in detecting anomalies and reduces the false-positive rate.

A hybrid approach was developed in this study [14] to cluster and route data. To reduce energy consumption and maintain reliable data transfer, machine learning and the Social Spider Optimization (SSO) technique will be used. This study demonstrates that bio-inspired techniques may be able to ensure that QoS is maintained in WSNs. To choose the optimal routes in 5G-enabled IoT-WSNs, the proposed work [15] introduced a model that combines Reinforcement Learning with ACO. The model combines the learning qualities of RL with the investigative skills of ACO to address the issues related to complex and rapid networks. This method minimizes complexity to provide accurate routing.

Table 1. Survey Table on Literature Works

Reference	Objective	Techniques Used	Primary works
[1]	Secure, energy-aware routing	Metaheuristic routing	Sustainable IoT-WSN with improved security and energy efficiency
[2]	Secure & efficient routing in IIoT	GA + ACO	Optimized routing for reduced energy & enhanced security
[3]	Secure route planning	Blockchain + Metaheuristics	Tamper-proof routing in hostile WSN environments
[4]	Comparative analysis	Conceptual	Explores similarities and gaps in IoT, WSN, and Sensor Cloud
[5]	IoT data flow management	Conceptual	WSNs as high-volume, real-time data sources in IoT
[6]	Data processing & analysis	Review-based	Covers fusion and filtering in IoT sensor networks
[7]	QoS-focused routing	Energy-aware protocols	Energy-efficient, delay-sensitive routing schemes
[8]	Critical applications	Energy-aware Routing	Role of WSNs in early warning & alert systems
[9]	QoS-aware service selection	Hybrid Metaheuristics	Enhances edge computing in IoT with optimized discovery
[10]	Energy conservation	Evolutionary + Swarm	Efficient offloading to extend WSN battery life

[11]	Charging path planning	Optimization + DL	Intelligent energy delivery to critical nodes
[12]	Cluster head selection	Whale Optimization	Efficient, scalable IoT node clustering
[13]	IoT security	Metaheuristics + ML	Improves anomaly detection in IoT/IoMT networks
[14]	Routing and clustering	ML + Social Spider Optimization	Boosts routing reliability and energy efficiency
[15]	Optimal path planning	RL + ACO	Reinforcement-learned ant routing in 5G-IoT WSNs

3. IoT-WSN Architecture

Everyone is aware that the Internet of Things (IoT) creates a vast number of interconnected devices by connecting sensors, actuators, and other intelligent devices. In order to detect, gather, and exchange data, these tools and devices connect with one another and the internet, frequently facilitating automation and remote access. Additionally, autonomous sensor nodes that are geographically dispersed to monitor environmental or physical conditions and wirelessly communicate sensor data are known as Wireless Sensor Networks (WSNs). Because they offer the essential element of sensing and data collection, WSNs are a crucial supporting technology for the Internet of Things. The limited data-gathering capabilities of a WSN are combined with the full connectivity and analysis capabilities of the Internet of Things in an IoT-WSN system.

Figure 3 shows an illustration of the IoT-WSN architecture. The figure depicts how the IoT-WSN functions and is connected. Data will be collected, maintained, or stored from the devices to a cloud database. The inputs will be sent via the internet to the gateway/edge computing from that specific cloud. The gateway functions similarly to a gate, allowing data to pass through to the specific sensors for authorization. Through the many branches and levels connected to the gateway, the data will be transferred. Finally, the sensors will take the data transmitted from the gateway and provide an accurate result.

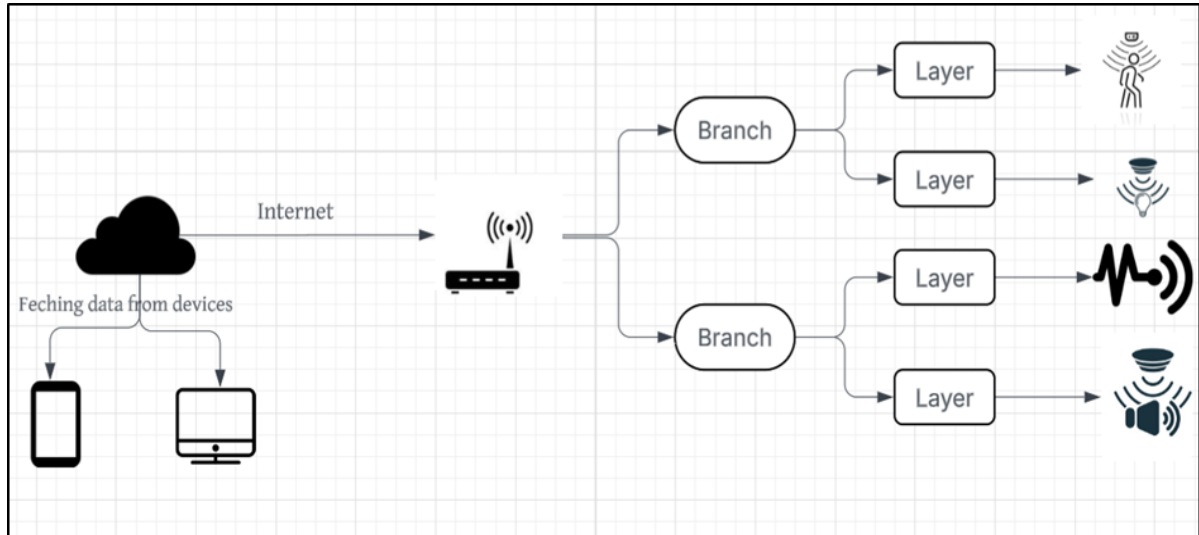


Figure 3. IoT-WSN Architecture

4. Metaheuristic Algorithm based Data Management Techniques

Different organizations may utilize the data to generate useful knowledge, preserve data integrity, function at scale, and also have this data organized in a way that is readable by various applications in an evolving big data environment. Traditional data management techniques were created long before it was feasible to represent data that is huge and dynamic, making it difficult to handle these large datasets. Now, efficient metaheuristic algorithms are used in this approach to make it useful for managing large sets of data. Based on this method and by using these patterns, the metaheuristic algorithm solves the optimization issues found in the data management process. Metaheuristic algorithms are “high-level” approaches that don’t depend on the specific issue being addressed. They aim to effectively communicate low-level heuristics for analyzing and taking advantage of the solutions. Because the complexity of the problems to be solved makes exact techniques computationally impossible to operate, metaheuristic algorithms are particularly useful for NP-hard situations. The well-known Metaheuristic algorithms are given below: -

- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Ant Colony Optimization (ACO)
- Firefly Algorithm (FA)
- Grey Wolf Optimizer (GWO)

- Whale Optimization Algorithm (WOA)
- Differential Evolution (DE)

4.1 Data Management Techniques

The process of obtaining, storing, organizing, and preserving the data generated and gathered in organizations is known as data management. Accuracy in the system is guaranteed by efficient data analysis techniques.

- **Clustering**

An unsupervised machine learning method called clustering is utilized to organize raw data into groups based on their similarity to one another. (This type of grouping is known as classification if the situations are identified.) Consider a fake patient study designed to evaluate an innovative method of treatment. Patients are required to keep track of the severity and frequency of their symptoms throughout the research. Patients behave similarly so treatments can be classified into groups by investigators using clustering analysis.

- **Routing**

The process of identifying a path in any network is called routing. Several machines, referred to as nodes, and the pathways or links that connect them create a computer network. In an interconnected network, there are numerous ways for two nodes to communicate with one another. The process of selecting the most effective course path based on an array of predefined conditions is called routing.

- **Data Aggregation**

The process of collecting large amounts of data from a database and organizing it into an easier-to-understand and extensive design is known as data aggregation. From pivot lists to data pools, data aggregation may be used at any level to gather information and develop findings from data that are loaded with information. The usage of data aggregation has become more necessary due to the increasing accessibility of information and the value of customization measures within the organization. The use case is not limited to the industry and is often essential to the execution and ongoing improvement of organizational operations everywhere.

- **Task Scheduling**

In the field of computing, task scheduling is the process of assigning virtual machines to fulfill user requests while considering a number of variables and constraints. Resource optimization, system throughput, energy conservation, cost reduction, and handling time reduction are the primary goals. The constant submission of different tasks and the rapid increase in people using cloud services result in a challenging issue in cloud computing. In order to achieve several objectives within the allotted period and without operating under the service level agreement, effective task scheduling techniques are required.

- **Energy Efficiency**

Developing a sustainable future requires energy efficiency, and improving data center energy usage is an essential part of this project. This involves maintaining computer systems and devices performing effectively with minimizing waste and unnecessary energy use. Users may decrease operating costs and the environmental impact of data centers by improving their electrical efficiency. Improving the cooling systems and using more energy-efficient hardware and software are two methods of achieving this goal. Implementing data center energy efficiency is an important goal that could support the development of a future digital network offering more energy-efficient and environmentally friendly.

5. Comparative Analysis

In Internet of Things (IoT)-based Wireless Sensor Networks (WSNs), energy efficiency, scalability, latency, and adaptability are important, metaheuristic algorithms have evolved into efficient methods for optimizing data handling operations. The Firefly Algorithm (FA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) are some of the most commonly used methods. Depending on the WSN's features and its data management issues, each of these approaches has unique benefits and drawbacks.

5.1 Genetic Algorithm (GA)

Clustering, task scheduling, and energy balancing are some of the complicated optimization problems that the Genetic Algorithm (GA) is quite effective at handling. GA simulates the process of random selection. Its advantage is the ability to explore broadly and

adapt to complex problems. However, particularly if implemented in large-scale dynamic networks, it often experiences slow resolution and higher computational expenses.

5.2 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is well-known for its rapid convergence and reduced computational expense. It was developed based on the social interactions of fish communities and flocks of birds. PSO performs well in variable applications, making it suitable for real-time applications like cluster head (CH) selection and routing. However, PSO might struggle to identify the optimal global condition due to a tendency for early convergence, particularly in multi-modal research areas.

5.3 Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is particularly suitable for routing and path planning in WSNs, depending on the food consumption habits of ants. ACO can adapt to changing network structures by establishing multiple routes and using regular updates to enhance the most effective routes. However, as the network develops, this adaptation comes at the cost of increased memory utilization and communication delays.

5.4 Firefly Algorithm (FA)

The Firefly Algorithm (FA) works effectively for dynamic optimization problems including fault-tolerant clustering and node localization based on the displaying movements of fireflies. FA uses relatively few control settings and performs well in local search queries. In many situations, it merges the data faster than GA and ACO, even though it may not consistently approach PSO in this area.

[Note: In this table 2, each data is marked as number to symbolize those words. Excellent means 7; High means 6; Very good means 5; Good means 4; Moderate means 3; limited use means 2; Bad means 1; very bad means 0]

Table 2. Different Metaheuristic Algorithms Performs in Data Management Process

Data Management Function	Genetic Algorithm	Particle Swarm Optimization	Ant Colony Optimization	Firefly Algorithm
Clustering	7	5	3	7
Routing	3	7	7	4

Data Aggregation	4	4	7	4
Task Scheduling	7	3	2	3
Energy Efficiency	3	6	3	6
Latency Minimization	3	6	3	4
Scalability	4	7	3	4
Fault Tolerance	3	3	6	6

In general, the specific data management goals and limitations of the IoT-WSN application should influence the selection of the approach. Overall, complex optimization is better handled by GA; low-latency and energy-efficient operations are more effectively managed by PSO; dependable, adaptive routing can be provided by ACO; and adaptable and resilient clustering or fault management tasks are well handled by FA.

From the above, Table 1 represents the performance of data techniques in different metaheuristic algorithms, which has been converted into a figure format for easier understanding. Figure 4 represents the overall performance of data techniques in algorithms related to data handling. From the diagram, the overall better performance is achieved by the Firefly Algorithm (FA), which shows better results in data management techniques compared to the Genetic Algorithm (GA).

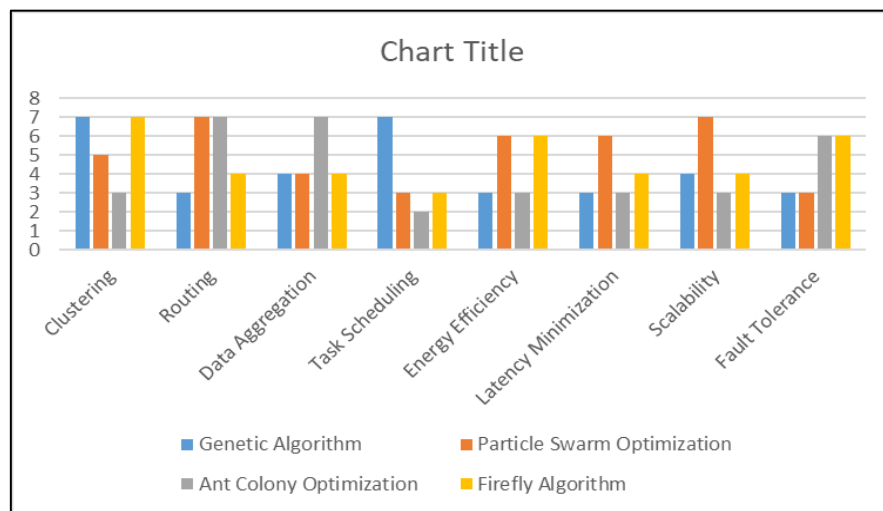


Figure 4. Performance of Algorithms in Data Management

6. Conclusion

Metaheuristic Algorithms are an efficient approach for handling data management issues in IoT-WSNs. They are suitable for evolving and resource-limited networks because of their adaptability and capacity to detect almost optimal approaches in challenging conditions. Metaheuristic techniques have the ability to substantially enhance the performance and sustainability of future IoT-WSN deployments with additional improvements in hybridization and computational effectiveness. Data aggregation, routing, clustering, and various data management techniques benefit from the high optimization capabilities of metaheuristic algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Firefly Algorithm (FA). In the case of highly dimensional and complex search spaces, these algorithms provide a flexible structure that can find optimal solutions in manageable computing timeframes. WSNs can achieve improved energy efficiency, prolonged network lifetime, decreased data redundancy, and more accurate data by applying the research and utilization capabilities of metaheuristics. Additionally, new possibilities for context-aware, real-time data processing and intelligent decision-making have been made possible by hybrid metaheuristic techniques integrating with machine learning models.

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