Nature-Inspired Metaheuristic Optimization for Network Design and Communication Systems: Trends, Applications, and Future Directions

Hussein Ibrahim Hussein[1,2,*], Lateef Abd Zaid Qudr[1], Weal Hasan Ali Almohammed[3]

[1] Department of Computer Engineering Techniques, Alsafwa University College, Karbala, Iraq
[2] Department of Information Security, College of Information Technology, University of Babylon, Hillah, Iraq
[3] Department of Computer Science, College of Computer Science and IT, University of Kerbala, Iraq
Emails: Hussein.sarhan@alsafwa.edu.iq; latifkhder@alsafwa.edu.iq; wael.h@uokerbala.edu.iq

Abstract

Communication network design (CND) and wireless sensor networks (WSNs) presents significant challenges, particularly in optimizing network reliability, energy efficiency, and cost-effectiveness. This literature review discusses using metaheuristic algorithms to solve the mentioned NP-hard problems and provide accurate results for network reliability, resource management assignment, and energy utilization in data transmission networks. Recent advancements in hybrid metaheuristic approaches, such as combining Genetic Algorithms with Branch and Bound (GA-BB) or Particle Swarm Optimization with Simulated Annealing (PSO-SA), demonstrate their effectiveness in optimizing network performance in emerging domains like vehicular ad-hoc networks (VANETs) and Internet of Things (IoT)- enabled WSNs. The review also discusses the application of optimization approaches about distinct issues such as cluster head selection in WSNs, routing protocols in dynamic networks, and supply chain network design. These developments are essential in evolving technologies such as 6G networks and the Internet of Everything (IoE), where complex systems demand innovative optimization strategies. By highlighting these concerns in the current study, this review calls for the increased use of metaheuristic techniques towards furthering the application of future networks in smart cities, healthcare, and secure network architectures.

Keywords: Metaheuristic algorithms; Wireless Sensor Networks; Communication Network Design; Energy efficiency; Network reliability

1. Introduction

Communication systems and network infrastructure are constantly evolving. The design tasks are now significantly larger and more complex; therefore, specialized optimization methods are required to help explore the numerous available design alternative.in network design, which encompasses bandwidth allocation, routing, quality of service, and energy management, traditional optimization methods often fail to address the complex and intricate nature of these problems [**?**, 1]. Metaheuristic optimization algorithms have been shown to solve these problems more effectively than traditional deterministic techniques by drawing inspiration from nature and utilizing different evolutionary and swarm-based mechanisms [2].

The use of metaheuristic optimization techniques in network design and communications has become increasingly common, as these methods are effective in handling complex problems and finding highly efficient solutions within reasonable computational time [3, 4]. Using algorithms such as Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization, as well as their hybrid versions, researchers have addressed various networking challenges, including wireless sensor deployment and large-scale telecommunication planning. Among optimization techniques, metaheuristics are particularly useful in dynamic networks because traditional solutions struggle with constant changes in network structure, traffic behavior, and resource usage [5, 6].

Improvements in signal processing and machine learning have led to stronger results when using metaheuristic optimization for networking [7]. The combination of these technologies enables better optimization functions, more effective constraint handling, and automatic parameter regulation, ultimately improving overall performance. Deep learning methods have also made it possible to develop frameworks that can learn from historical network performance data and guide heuristic searches

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

toward promising solution regions.

Many issues in network design, from early planning stages to highly customized communication protocols, can be solved using metaheuristics. Such applications include network topology design, resource allocation, optimal routing, load balancing, resilience enhancement against failures, and security configuration management. Since network design problems often require balancing several competing objectives, metaheuristic algorithms are beneficial for addressing multi-objective optimization problems.

Furthermore, the emergence of next-generation networks, including 5G/6G wireless systems, Internet of Things (IoT) deployments, and edge computing architectures, has created new optimization challenges that benefit significantly from metaheuristic approaches. These modern network paradigms require optimization solutions that can adapt to heterogeneous environments, handle massive device connectivity, and ensure reliable performance under varying operational conditions. Advanced signal processing techniques integrated with machine learning have shown promising results in addressing these complex optimization scenarios.

When metaheuristic algorithms are used in conjunction with modern computational methods, they enable the solution of network design problems that were previously very difficult. Using both generic and customized optimization approaches allows these methods to overcome individual limitations and deliver better results for modern communication systems.

This survey aims to review metaheuristic optimization in network design and communication systems by highlighting recent progress, modern approaches, and promising research topics in this rapidly developing field. Figure 1 presents a comprehensive conceptual overview of the role of metaheuristic optimization in modern network design and communication systems. The illustration highlights how nature-inspired and population-based optimization techniques can be applied to address complex network challenges, including high dimensionality, dynamic topology changes, uncertainty, and multi-objective requirements. It also demonstrates the general workflow from problem formulation to solution evaluation, showing how algorithms such as Genetic Algorithm, Particle Swarm Optimization, Ant Colony Optimization, Whale Optimization Algorithm, Grey Wolf Optimizer, Simulated Annealing, and Harris Hawks Optimization can support optimal or near-optimal network design. Overall, the figure emphasizes that metaheuristic optimization contributes to improved performance, energy efficiency, cost reduction, scalability, reliability, security, and sustainability in next-generation communication systems.

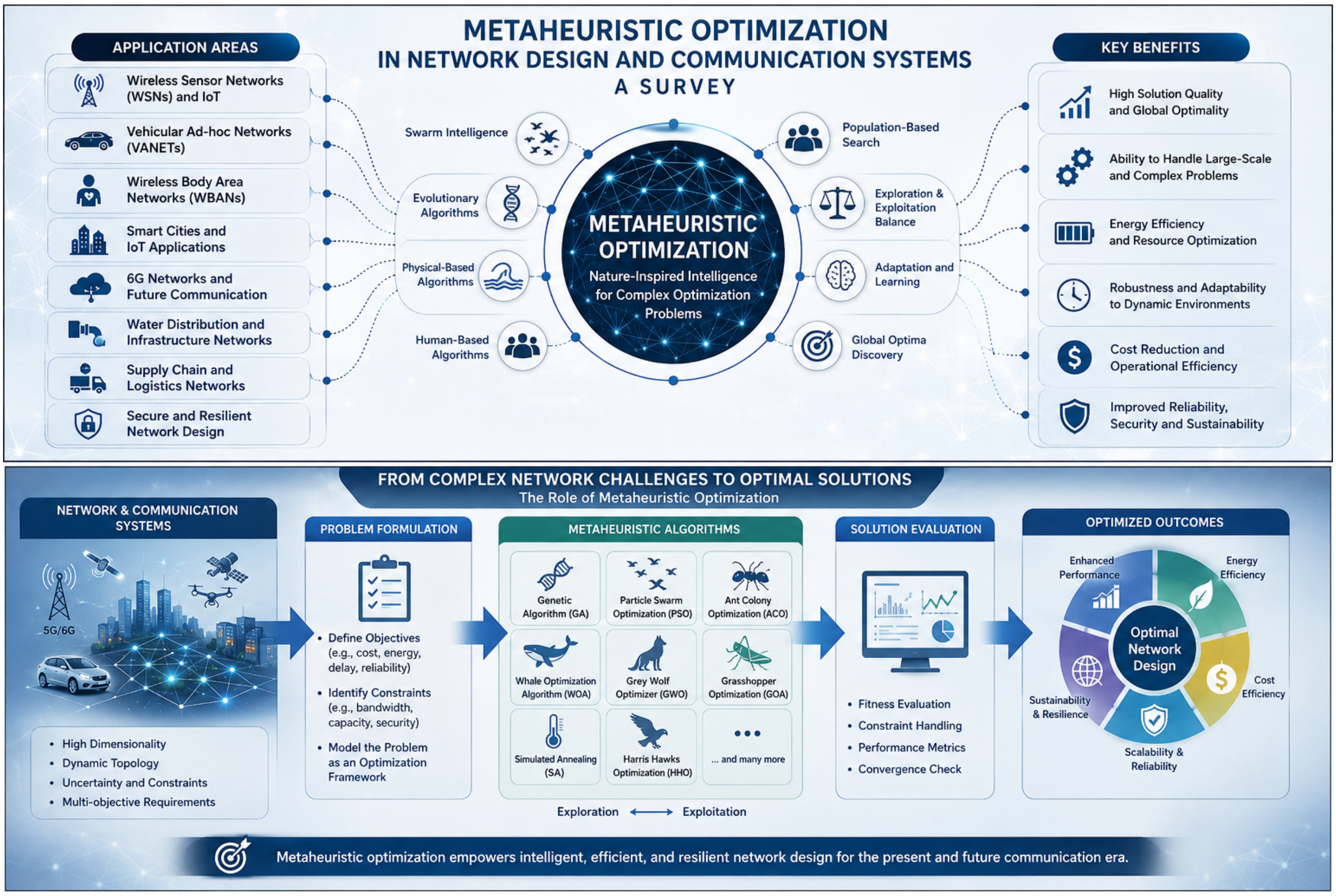

Figure 1. Conceptual overview of metaheuristic optimization applications in network design and communication systems. The figure illustrates the main application domains, including wireless sensor networks, vehicular ad-hoc networks, IoT-based smart systems, 5G/6G communication environments, secure network design, and infrastructure networks. It also summarizes the key benefits of metaheuristic optimization, such as energy efficiency, cost reduction, reliability enhancement, scalability, and robustness in dynamic environments.

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

2. Related Work

The fields of Communication Network Design (CND) and Wireless Sensor Networks (WSNs) face significant optimization challenges, particularly in enhancing network reliability, energy efficiency, and cost reduction. Metaheuristic algorithms are instrumental in solving these NP-hard problems and have been widely used to address network reliability and efficient resource provisioning. Recent studies have proposed several hybrid metaheuristic techniques for improving network capacity, reducing energy consumption, enhancing routing algorithms, and managing dynamic topologies in emerging networks such as vehicular and flying ad-hoc networks. These developments are increasingly important in the Internet of Things (IoT) and 6G networks, where the complexity of modern systems requires innovative optimization strategies. The following literature review provides an enhanced understanding of state-of-the-art technologies and their adaptation in smart cities, healthcare systems, supply chain systems, and secure network design.

Reliable Communication Network Design (RCND) is a well-recognized optimization challenge that aims to maximize network reliability. The study in [8], for example, focuses on reducing the cost of a communication network while ensuring the required reliability of all terminals. Due to the NP-hard nature of this problem, diverse metaheuristic algorithms have been widely applied. The study proposes two hybrid algorithms, namely GABB and SABB, which combine Genetic Algorithm (GA) or Simulated Annealing (SA) with the Branch and Bound (B&B) method. These hybrid methods improve solution quality by fine-tuning or repairing infeasible solutions and achieve better results than basic GA, SA, and other techniques previously studied in the literature.

Clustering is a crucial technique for enhancing network lifetime in Wireless Sensor Networks (WSNs). In [9], sensor nodes are grouped into clusters, and Cluster Heads (CHs) are selected to collect data and forward it to the Base Station (BS). However, efficient CH selection remains a critical issue because sensor nodes consume more energy during data transmission, which reduces network lifetime. To overcome this problem, clustering is used to support efficient transmission, conserve energy, and extend network lifespan. The paper presents an enhanced CH selection mechanism using hierarchical routing and a hybrid optimization method for energy-aware communication. Specifically, the Particle Distance Updated Sea Lion Optimization (PDU-SLnO) algorithm, which combines Sea Lion Optimization (SLnO) and Particle Swarm Optimization (PSO), is proposed for optimal CH selection by considering energy, distance, delay, and Quality of Service (QoS). A comparative analysis is conducted using different performance measures against conventional models.

In Vehicular Ad-Hoc Networks (VANETs), vehicles act as mobile nodes that communicate while continuously moving, causing dynamic changes in network topology. As established in [10], this creates scalability issues and complicates the search for optimal communication paths, especially in high-density environments. These challenges are commonly addressed using clustering protocols. The study introduces a Grasshopper Optimization Algorithm (GOA)-based node clustering method for optimal cluster-head selection in VANETs. In environments where node density is difficult to predict, the GOA algorithm minimizes overall network overhead. Various experiments compare GOA with other techniques, including Dragonfly Algorithm, Grey Wolf Optimizer (GWO), and Ant Colony Optimization (ACO). Based on parameters such as the number of clusters, network area, node density, and transmission range, the authors demonstrate that GOA outperforms the compared methods. The potential application of GOA in Flying Ad-Hoc Networks (FANETs) for next-generation networks is also proposed.

Technological advancements in Wireless Body Area Networks (WBANs) have enabled the design of numerous sensing modules that monitor different physical attributes of a patient's body. The study in [11] identifies restricted battery lifespan as a major barrier to WBAN performance. To address this issue, the paper proposes a Novel Energy-Efficient Hybrid Meta-Heuristic Approach (NEEMA), which aims to reduce energy consumption in sensor nodes. The proposed hybrid algorithm combines the Tunicate Swarm Algorithm (TSA) with the Genetic Algorithm (GA), forming T-GA. This hybrid method offers high convergence rates and strong exploration and exploitation capabilities. The approach selects Cluster Heads (CHs) using a fitness function based on novel energy-efficiency parameters. The work also incorporates multi-hop communication, where body sensor data is relayed through Relay Head (RH) nodes until it reaches healthcare providers. The RH selection process is similar to CH selection in order to minimize energy consumption during data transmission. Experimental evaluation demonstrates that NEEMA outperforms existing methods and may be beneficial for different WBAN applications.

Energy efficiency is a critical design challenge in Wireless Sensor Networks (WSNs), and it can be addressed through clustering and routing techniques. These techniques are generally considered NP-hard optimization problems; therefore, heuristic and metaheuristic algorithms are commonly used to obtain near-optimal solutions [12]. Motivated by this, the study presents a Hybrid Metaheuristic Cluster-Based Routing (HMBCR) technique for WSNs. The HMBCR approach begins with a clustering process using Brainstorm Optimization with Levy Distribution (BSO-LD), relying on a fitness function that considers energy, distance to neighbors, distance to the base station, and network load. The routing process then employs Water Wave Optimization with Hill-Climbing (WWO-HC) to select the optimal route. The algorithms are validated through rigorous experiments, confirming improved energy efficiency and network lifetime compared with other techniques.

In recent trends, IoT-enabled Wireless Sensor Networks have become essential for emergency medical services, fire detection, and flood control applications in smart cities. According to [13], sensor devices are highly energy-constrained due to limited battery resources, especially when data is collected for disaster management applications. Several issues, such as cluster

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

overlapping, selection of low-energy nodes as cluster heads, formation of highly dense clusters, hotspot problems, and long communication distances, further increase energy consumption. To address these challenges, the study proposes an integrated modified Genetic Algorithm for CH election, called ModifyGA, to maximize network lifetime. ModifyGA improves energy management by integrating dynamic sensing ranges and optimizing the fitness function according to intra-cluster distance constraints, node energy usage, and minimum hop count. Simulation evaluation considers single static sinks, multiple static sinks, and movable sinks, showing better energy utilization and network quality than other algorithms.

There has also been considerable interest in improving supply chain networks. In [14], the authors introduce a new model for optimizing a closed-loop supply chain network using two-stage stochastic programming. The robust optimization framework captures uncertainty in product manufacturing, customer demand, pricing, and return rates, while considering financial risk as an objective function. To solve the model, the study employs the Whale Optimization Algorithm (WOA), a recent nature-inspired approach, and compares it with Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Simulated Annealing (SA). The study uses Response Surface Methodology (RSM) for fair parameter tuning of the algorithms. Evaluation metrics are used to measure the quality of the Pareto optimal front, and statistical and sensitivity analyses are performed using an industrial case study.

Power conservation is a serious issue in the design of routing algorithms for Wireless Sensor Networks. In [15], the authors propose a routing algorithm intended to maximize network lifetime using an elite hybrid metaheuristic optimization solution. This method combines the global search capabilities of Particle Swarm Optimization, the difference operator from Differential Evolution, and pheromone-based strategies from Ant Colony Optimization. This integrated approach helps prevent the algorithm from becoming trapped in local optima while maintaining population diversity and accelerating convergence toward optimal solutions. Simulation analysis shows that the proposed routing algorithm improves network lifetime by 38% compared with existing routing methods based on other population-based optimization techniques.

Accurate sensor-node location information is important for location-based services in Wireless Sensor Networks. In [16], range-based localization is investigated as a two-dimensional optimization problem and solved using a multistage bio-inspired metaheuristic approach. The study introduces a modified version of the Shuffled Frog Leaping Algorithm (MSFLA) specifically designed for precise sensor localization. The performance of MSFLA is compared with geometric trilateration, Artificial Bee Colony, and Particle Swarm Optimization, focusing on localization accuracy under environmental noise. Simulation results suggest that MSFLA improves localization accuracy by more than 30% compared with geometric trilateration in noisy environments. However, the study also notes that MSFLA requires more computational time and effort than other compared methods.

The rapid advancement of sixth-generation (6G) networks and the Internet of Everything (IoE) is enabling many emerging services and applications. As mentioned in [17], increasing demand has introduced new challenges that current network architectures cannot fully address. To overcome these problems, the concept of a cyber twin has been proposed, providing features such as communication support, network data logging, and digital asset management. Since spectrum resources are limited, efficient control and utilization of the available spectrum remain major challenges. The paper proposes a metaheuristic resource allocation technique, MWBA-RAT, incorporating blockchain for efficient monitoring, management, and resource sharing in 6G networks. The MWBA-RAT technique introduces a Quasi-Oppositional Search and Rescue Optimization (QO-SRO) algorithm for optimal resource allocation. By incorporating quasi-oppositional learning into the SRO algorithm, the method aims to improve convergence speed. Experimental results show that MWBA-RAT outperforms existing methods.

Software-Defined Wireless Sensor Networks (SDWSNs) provide an architecture that enables self-configurable, scalable, and programmable control features. As described in [18], the network structure is divided into the data plane and the control plane. In the data plane, Normal Nodes (NNs) handle data collection and processing, while Control Nodes (CNs) in the control plane route data from NNs to neighboring CNs and the Control Server (CS) according to programmed instructions. To achieve Quality of Service (QoS) parameters, CNs are dynamically selected and strategically positioned. However, CNs consume significant energy and operate on limited battery capacity. To address this challenge, the study introduces a green computing-aware multi-objective solution for the CN placement problem using a metaheuristic approach that considers energy consumption, distance, and load imbalance. The proposed method uses Multi-Objective Harris Hawks Optimization (MOHHO) to obtain optimal outcomes. Simulation results demonstrate improved energy usage, reduced load imbalance, minimized delay, and extended SDWSN lifetime.

Modern developments in Wireless Sensor Networks have made indoor wireless communication more reliable and versatile, especially within large buildings or groups of buildings. The node localization process is described in [19], where the coordinates of unknown nodes are calculated based on known anchor-node coordinates. Previous work has shown that node localization is computationally NP-hard. Therefore, several heuristic algorithms have been applied to reduce localization error. The study proposes a new metaheuristic algorithm called the Group Teaching Optimization Algorithm for Node Localization (GTOA-NL). The algorithm is inspired by group teaching techniques and is suitable for optimization while maintaining general applicability. Simulation tests validate the effectiveness of GTOA-NL under varying conditions involving the number of anchor nodes, ranging errors, and transmission ranges.

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

The Internet of Things is increasingly applied in smart cities, agriculture, weather forecasting, smart grids, and waste management. In [20], the authors note that although IoT has diverse applications, it also faces challenges such as optimizing sensor energy consumption to extend network lifetime. The study focuses on optimizing energy consumption by selecting the most appropriate Cluster Head within the IoT network. This is achieved through a hybrid metaheuristic algorithm that combines Whale Optimization Algorithm with Simulated Annealing. The proposed method optimizes CH selection using parameters such as the number of active nodes, load balancing, temperature, residual energy, and cost functions. The performance is compared with Artificial Bee Colony Algorithm, Genetic Algorithm, Adaptive Gravitational Search Algorithm, and WOA. The results show that the proposed hybrid method improves energy efficiency in IoT networks.

Parkinson's disease is a chronic nonfatal illness characterized by progressive deterioration of the motor system of the central nervous system. In [21], the authors conduct comparative studies using AutoEncoder and Ant Colony Optimization feature selection algorithms to identify effective features for Parkinson's disease diagnosis. The algorithms are applied to a voice dataset obtained from an online repository, and the selected features are evaluated using classifiers such as Decision Tree, Support Vector Machine, K-Nearest Neighbors, Ensemble methods, Naive Bayes, and Discriminant classifiers. The system performance is evaluated using sensitivity, specificity, precision, recall, and accuracy. Classifier 1 and Classifier 2 are trained and tested individually to compare feature selection techniques for distinguishing between control and Parkinson's disease groups. The study indicates that although ACO and AutoEncoder produce similar training errors with K-NN and Ensemble classification, ACO achieves slightly higher testing accuracy.

Water Distribution Networks (WDNs) are vital infrastructures that transport potable water to communities. They consist of various components and require significant financial investment for their design. As outlined in [22], WDNs face hydraulic and mechanical risks that can cause partial or complete failure during their service life. Therefore, design strategies must balance reliability and cost. The study develops a reliability-based metamodel-integrated optimization model for WDN design optimization. This framework consists of an optimization model, a simulation model, and a reliability evaluation model. The study employs a hybrid technique combining Differential Evolution (DE) and the Krill Herd Algorithm (KHA), called DE-KHA, to solve WDN design problems by balancing exploration and exploitation. EPASPEC 2.0 is used for hydraulic simulation, while a reliability model based on the Minimum Cut Set method evaluates mechanical availability. The framework is validated using a Two Loop Network consisting of eight pipes and seven nodes supplied by one reservoir. The results show an optimal design cost of $419,000, demonstrating the applicability of the model to reliable WDN design.

Another important task in contemporary information technology is ensuring correct network structure design. According to [23], conventional approaches may be less effective in handling the increasing complexity and volatility of security threats. Metaheuristic optimization techniques have emerged as promising solutions because they can efficiently search complex spaces to find improved network configurations that enhance security. The study reviews metaheuristic optimization algorithms used in secure network design and analyzes their suitability, usefulness, operations, and applications. Through case studies and comparative analysis, the study demonstrates how metaheuristic approaches can reduce security threats, improve network stability, and support secure network architectures.

Due to increasing uncertainty in complex environments, strategic planning for sustainable supply chains has become an important requirement. As noted in [24], supply chain management must balance economic objectives with environmental and social sustainability. Competitive advantage depends on reducing operational costs while increasing service delivery levels. The study presents a multi-objective model for sustainable closed-loop supply chain network design. The model considers total cost, social sustainability, environmental impact, and both forward and reverse flows. Because sustainable closed-loop supply chain network design is a multifaceted problem with several objectives, innovative solution approaches are required. The study applies the Red Deer metaheuristic algorithm, along with two advanced algorithms and two basic algorithms. Comparative results demonstrate the efficiency and effectiveness of the Red Deer algorithm for solving complex closed-loop supply chain problems.

Recently, the Internet of Medical Things (IoMT) has emerged as a promising technology for interconnected healthcare networks. Based on [25], IoMT frameworks respond to changing patient conditions and help identify rare health conditions using collected data. Metaheuristic algorithms provide efficiency, reliability, and flexibility in solving real-world problems such as optimization, clustering, forecasting, and classification. However, the growth of big data from the web, sensors, and social media introduces new challenges for metaheuristic algorithms. The study presents a metaheuristic optimization approach for big data analysis in IoMT using a Gravitational Search Optimization Algorithm (GSOA) with Deep Belief Networks and Convolutional Neural Networks (DBN-CNNs). The model focuses on improving diabetes-related data analysis and predicting cardiac risk using Support Vector Machine (SVM) techniques. Performance analysis shows that the GSOA-DBN-CNN model improves accuracy, precision, recall, F1-score, and Peak Signal-to-Noise Ratio (PSNR).

The optimization of gravity-fed Water Distribution Network Design (WDND) involves selecting appropriate pipe diameters to satisfy hydraulic constraints while minimizing total cost. As illustrated in [26], when network size increases, heuristic solutions based on expert knowledge are often far from optimal. Over the past three decades, various approaches have been proposed for integral water distribution network design. The paper focuses on the multi-period WDND optimization problem under

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

dynamic demand conditions, which is NP-hard. The authors propose an enhanced simulation-based Iterated Local Search (ILS) metaheuristic that uses problem-structure knowledge to generate high-quality solutions. The approach introduces four innovations: a local search strategy that dimensions pipes along the shortest paths between reservoirs and high-demand nodes; an aggressive pipe diameter reduction method to accelerate convergence; a concentrated perturbation mechanism to escape constrained local optima; and a solution pool balancing intensification and diversification. Numerical simulations show that this method outperforms a benchmark metaheuristic by achieving lower-cost solutions with less variability.

The problem of selecting optimal machine trail network locations is a location problem involving trade-offs among operational, topographical, and machine-related factors. In [27], the authors aim to reduce logging operation costs by developing an integer programming model for trail network design. They propose a greedy heuristic algorithm that uses randomized search contexts to identify suitable machine trail locations while reducing environmental impacts. The model considers tree access, machine movement, and terrain altitude differences. An empirical study evaluates the feasibility and efficiency of the heuristic and optimization model across four harvest units with different geometries and layouts. The results show that the heuristic method consistently produces better solutions than manual designs within reasonable computational time. The study also provides a computational sensitivity analysis to examine the behavior of the heuristic under different parameter settings.

The improvement of communication and sensor networks remains an active research area because of the need for greater efficiency, dependability, and reduced energy consumption. The development of new metaheuristic algorithms, such as Genetic Algorithm combined with Branch and Bound or PSO combined with Simulated Annealing, shows significant improvements compared with conventional methods. These algorithms offer practical solutions to different problems in WSNs, VANETs, and supply chain networks. Therefore, continued advancement and research on metaheuristic algorithms will remain important for addressing complex optimization challenges in future technologies such as IoT and 6G networks. This literature review presents ongoing efforts to improve these algorithms and highlights their potential to shape the future of network architecture and resource management.

Table 1 provides an overview of recent applications of metaheuristic algorithms in CND, WSNs, and other domains such as supply chains, healthcare, and smart-city infrastructure. Each row presents the reference, focus area, proposed method, and main contribution of the corresponding study.

Table 1. Comparative Summary of Recent Metaheuristic Optimization Approaches for Network Design, Communication Systems, and Related Applications

Ref.	Focus Area	Proposed Method	Main Contribution
[8]	Reliable Communication Network Design (RCND)	Hybrid GA/SA with Branch & Bound	Improves network reliability and cost-efficiency through hybridization and infeasible-solution repair.
[9]	Wireless Sensor Networks (WSNs): Clustering	PDU-SLnO: Sea Lion Optimization and PSO	Provides energy-aware cluster-head selection using hierarchical routing while considering energy, distance, delay, and QoS.
[10]	Vehicular Ad-Hoc Networks (VANETs)	Grasshopper Optimization Algorithm (GOA)	Enables optimal clustering under high mobility and dynamic topology conditions, reducing overall network overhead.
[11]	Wireless Body Area Networks (WBANs)	T-GA: Tunicate Swarm Algorithm and Genetic Algorithm	Enhances energy-efficient cluster-head and relay-head selection for healthcare-oriented WBAN applications.
[12]	Hybrid Routing in WSNs	HMBCR: BSO-LD and WWO-HC	Improves clustering and routing performance by combining brainstorm optimization, Levy distribution, water wave optimization, and hill climbing.
[13]	IoT-enabled WSNs in Smart Cities	ModifyGA	Extends network lifetime and improves energy utilization in disaster-management scenarios using modified genetic-based cluster-head election.
[14]	Closed-Loop Supply Chain Optimization	Whale Optimization Algorithm (WOA)	Supports robust and risk-sensitive supply chain network design under uncertainty using calibrated metaheuristic optimization.
[15]	Routing in WSNs	Hybrid PSO, Differential Evolution, and ACO	Extends wireless sensor network lifetime by improving global search, maintaining population diversity, and avoiding local optima.
[16]	Sensor Localization in WSNs	Modified Shuffled Frog Leaping Algorithm (MSFLA)	Improves node localization accuracy in noisy environments compared with deterministic and other metaheuristic approaches.
[17]	6G Networks and Resource Allocation	MWBA-RAT: QO-SRO and Blockchain	Provides efficient resource allocation in cyber-twin-driven 6G and IoE environments through blockchain-supported optimization.
[18]	Software-Defined Wireless Sensor Networks (SDWSNs)	Multi-Objective Harris Hawks Optimization (MOHHO)	Optimizes control-node placement by reducing energy consumption, delay, and load imbalance in SDWSNs.
[19]	Indoor Node Localization	Group Teaching Optimization Algorithm for Node Localization (GTOA-NL)	Provides robust indoor node localization under varying anchor-node numbers, ranging errors, and transmission ranges.

Continued on next page

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

Table 1 continued from previous page

Ref.	Focus Area	Proposed Method	Main Contribution
[20]	IoT Cluster-Head Optimization	Hybrid WOA and Simulated Annealing	Optimizes cluster-head selection to improve energy efficiency, load balancing, and active-node sustainability in IoT networks.
[21]	Parkinson's Disease Detection via Voice	AutoEncoder and Ant Colony Optimization	Supports effective feature selection for disease classification using voice-signal data and machine-learning classifiers.
[22]	Water Distribution Network Design (WDN)	DE-KHA: Differential Evolution and Krill Herd Algorithm	Provides reliable and cost-effective WDN design by balancing hydraulic performance, mechanical reliability, and design cost.
[23]	Secure Network Design	Metaheuristic-based Secure Design	Reviews the use of metaheuristic optimization for improving network security, stability, and architectural resilience.
[24]	Sustainable Closed-Loop Supply Chain	Red Deer Algorithm	Supports sustainable and economic supply chain network design using a multi-objective optimization framework.
[25]	IoMT Disease Prediction	GSOA with DBN-CNN	Improves disease prediction accuracy in Internet of Medical Things environments using metaheuristic optimization and deep learning.
[26]	Multi-period Water Distribution Network Design	Enhanced Iterated Local Search (ILS) Metaheuristic	Achieves low-cost dynamic WDN optimization using local search, pipe-diameter reduction, perturbation, and solution-pool mechanisms.
[27]	Machine Trail Network Design	Greedy Heuristic Algorithm	Enables cost-efficient logging trail placement while considering terrain, machine movement, and environmental constraints.

The variety of techniques, including hybrid Genetic Algorithms, Simulated Annealing, and modern swarm-intelligence approaches such as Whale Optimization and Particle Swarm Optimization, indicates the need for interdisciplinary solutions to solve complex NP-hard optimization problems in modern networks. These approaches make it possible to reduce energy consumption, improve reliability, lower system costs, and increase robustness. These features are essential for 6G, IoMT, and resilient disaster-management systems in future smart cities.

3. Conclusion

The reviewed literature demonstrates the steady progress of metaheuristic optimization methods across different domains, including reliable communication networks, wireless sensor networks, vehicular ad-hoc networks, supply chain management, healthcare systems, and water distribution networks. As these systems continue to grow in scale and complexity, hybrid metaheuristic algorithms have proven effective in enhancing network reliability, energy efficiency, and system performance compared with traditional methods.

The integration of optimization algorithms, including Genetic Algorithms, Particle Swarm Optimization, and nature-inspired methods such as the Whale Optimization Algorithm and Tunicate Swarm Algorithm, has shown strong effectiveness in real-world applications involving resource allocation, clustering, routing, localization, and classification. These innovations create a foundation for improving efficiency in contemporary technologies such as IoT, 6G networks, and Health Information Technology.

The studies analyzed in this survey confirm that metaheuristic approaches hold significant promise for solving NP-hard problems and providing adaptive, reliable, and scalable solutions for future network structures and applications across different domains. Therefore, the continued enhancement and application of optimization algorithms will remain essential for the next generation of communication networks and intelligent systems.

References

[1] M. A. A. Calazans, F. A. B. S. Ferreira, F. A. N. Santos, F. Madeiro, and J. B. Lima, "Machine learning and graph signal processing applied to healthcare: A review," *Bioengineering*, vol. 11, no. 7, 2024.

[2] S. Chen, W. Sun, M. Ren, Y. Xie, and D. Zeng, "A hybrid model for monthly runoff forecasting based on mixed signal processing and machine learning," *Environmental Science and Pollution Research*, vol. 31, no. 57, pp. 65 866–65 883, 2024.

[3] T. Chen, "Can heart rate sequences from wearable devices predict day-long mental states in higher education students: a signal processing and machine learning case study at a uk university," *Brain Informatics*, vol. 11, no. 1, p. 29, 2024.

[4] P. Chinnasamy, G. C. Babu, R. K. Ayyasamy, S. Amutha, K. Sinha, and A. Balaram, "Blockchain 6g-based wireless network security management with optimization using machine learning techniques," *Sensors*, vol. 24, no. 18, 2024.

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

[5] T. S. Delwar, U. Aras, S. Mukhopadhyay, A. Kumar, U. Kshirsagar, Y. Lee, M. Singh, and J.-Y. Ryu, "The intersection of machine learning and wireless sensor network security for cyber-attack detection: A detailed analysis," *Sensors*, vol. 24, no. 19, 2024.

[6] S. Ekiz and U. Acar, "Improving building extraction from high-resolution aerial images: Error correction and performance enhancement using deep learning on the inria dataset," *Science progress*, vol. 108, no. 1, p. 00368504251318202, 2024.

[7] S. He, A. Baron, C. R. Munteanu, B. De Bilbao, G. M. Casanola-Martin, M. Chelu, A. M. Musuc, H. Bediaga, E. Ascencio, I. Castellanos-Rubio *et al.*, "Drug release nanoparticle system design: data set compilation and machine learning modeling," *ACS Applied Materials & Interfaces*, vol. 17, no. 3, pp. 5290–5306, 2024.

[8] O. Ozkan, M. Ermis, and I. Bekmezci, "Reliable communication network design: The hybridisation of metaheuristics with the branch and bound method," *Journal of the Operational Research Society*, vol. 71, no. 5, pp. 784–799, 2020.

[9] R. K. Yadav and R. P. Mahapatra, "Hybrid metaheuristic algorithm for optimal cluster head selection in wireless sensor network," *Pervasive and Mobile Computing*, vol. 79, p. 101504, 2022.

[10] W. Ahsan, M. F. Khan, F. Aadil, M. Maqsood, S. Ashraf, Y. Nam, and S. Rho, "Optimized node clustering in vanets by using meta-heuristic algorithms," *Electronics*, vol. 9, no. 3, 2020.

[11] S. Sharma, V. Mishra, and M. M. Tripathi, "A novel energy efficient hybrid meta-heuristic approach (neema) for wireless body area network," *International Journal of Communication Systems*, vol. 35, no. 13, p. e5249, 2022.

[12] S. Al-Otaibi, A. Al-Rasheed, R. F. Mansour, E. Yang, G. P. Joshi, and W. Cho, "Hybridization of metaheuristic algorithm for dynamic cluster-based routing protocol in wireless sensor networksx," *IEEE Access*, vol. 9, pp. 83 751–83 761, 2021.

[13] S. Singh, A. S. Nandan, A. Malik, N. Kumar, and A. Barnawi, "An energy-efficient modified metaheuristic inspired algorithm for disaster management system using wsns," *IEEE Sensors Journal*, vol. 21, no. 13, pp. 15 398–15 408, 2021.

[14] A. Abdi, A. Abdi, A. M. Fathollahi-Fard, and M. Hajiaghaei-Keshteli, "A set of calibrated metaheuristics to address a closed-loop supply chain network design problem under uncertainty," *International Journal of Systems Science: Operations & Logistics*, vol. 8, no. 1, pp. 23–40, 2021.

[15] H. Wang, K. Li, and W. Pedrycz, "An elite hybrid metaheuristic optimization algorithm for maximizing wireless sensor networks lifetime with a sink node," *IEEE Sensors Journal*, vol. 20, no. 10, pp. 5634–5649, 2020.

[16] V. R. Kulkarni, V. Desai, and R. V. Kulkarni, "A comparative investigation of deterministic and metaheuristic algorithms for node localization in wireless sensor networks," *Wireless Networks*, vol. 25, no. 5, pp. 2789–2803, 2019.

[17] D. K. Jain, S. K. S. Tyagi, N. Subramani, P. Mohan, and L. Natrayan, "MWBA-RAT: Novel approach for optimal resource allocation in 5G and beyond networks by cyber-twin-6G and blockchain technology," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 7, pp. 4884–4892, 2022.

[18] R. Chaudhry and N. Kumar, "A multi-objective meta-heuristic solution for green computing in software-defined wireless sensor networks," *IEEE Transactions on Green Communications and Networking*, vol. 6, no. 2, pp. 1231–1241, 2022.

[19] P. Sekhar, E. L. Lydia, M. Elhoseny, M. Al-Akaidi, M. M. Selim, and K. Shankar, "An effective metaheuristic based node localization technique for wireless sensor networks enabled indoor communication," *Physical Communication*, vol. 48, p. 101411, 2021.

[20] C. Iwendi, P. K. R. Maddikunta, T. R. Gadekallu, K. Lakshmanna, A. K. Bashir, and M. J. Piran, "A metaheuristic optimization approach for energy efficiency in the iot networks," *Software: Practice and Experience*, vol. 51, no. 12, pp. 2558–2571, 2021.

[21] B. Gergerli, F. V. Çelebi, J. Rahebi, and B. Şen, "An approach using in communication network apply in healthcare system based on the deep learning autoencoder classification optimization metaheuristic method," *Wireless Personal Communications*, pp. 1–24, 2023.

[22] S. Naga Poojitha and V. Jothiprakash, "Reliability-based hybrid metaheuristic optimization model for the design of two loop network under mechanical uncertain scenarios," in *EGU General Assembly Conference Abstracts*, 2022, pp. EGU22–12 971.

[23] A. Sagu, N. S. Gill, P. Gulia, P. K. Singh, and W.-C. Hong, "Design of metaheuristic optimization algorithms for deep learning model for secure iot environment," *Sustainability*, vol. 15, no. 3, 2023.

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025

[24] B. Karki, "Closed-loop supply chain network design optimization with a multi-objective approach: Leveraging the red deer metaheuristic algorithm."

[25] A. Sampathkumar, M. Tesfayohani, S. K. Shandilya, S. Goyal, S. Shaukat Jamal, P. K. Shukla, P. Bedi, and M. Albeedan, "Internet of medical things (iomt) and reflective belief design-based big data analytics with convolution neural network-metaheuristic optimization procedure (cnn-mop)," *Computational intelligence and neuroscience*, vol. 2022, no. 1, p. 2898061, 2022.

[26] W. C. Martinho, R. A. Melo, and K. Sörensen, "An enhanced simulation-based iterated local search metaheuristic for gravity fed water distribution network design optimization," *Computers & Operations Research*, vol. 135, p. 105429, 2021.

[27] A. Hosseini, E. Wadbro, D. Ngoc Do, and O. Lindroos, "A scenario-based metaheuristic and optimization framework for cost-effective machine-trail network design in forestry," *Computers and Electronics in Agriculture*, vol. 212, p. 108059, 2023.

DOI: https://doi.org/10.54216/JAIM.090107
Received: October 19, 2024 Revised: December 31, 2024 Accepted: January 27, 2025