فصلنامه نوآوری در مهندسی و تکنولوژی شماره 3- دوره 1- صفحات15-34
Journal of Innovation in Engineering and Technology

Application of Cuckoo Algorithm in Solving Routing Challenges in Internet of Things Networks

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Abstract

The Internet of Things (IoT) represents a transformative paradigm in modern networking, enabling the large-scale interconnection of heterogeneous devices ranging from sensors and actuators to complex embedded systems. With the continuous expansion of IoT deployments across domains such as smart cities, healthcare, and industrial automation, the demand for efficient, reliable, and scalable routing mechanisms has become increasingly critical. Conventional routing protocols, originally devised for traditional networks, struggle to accommodate the unique constraints of IoT environments, such as stringent energy limitations, high device density, dynamic topologies, and varying Quality-of-Service (QoS) requirements. These challenges necessitate the exploration and adoption of innovative, adaptive routing solutions. Nature-inspired optimization algorithms, especially the Cuckoo Optimization Algorithm (COA), have emerged as powerful alternatives for solving complex, dynamic problems in network design and management. Modelled on the brood parasitism behavior of cuckoo birds, COA offers global search capabilities, robust convergence characteristics, and flexibility in high-dimensional spaces, making it well-suited for addressing the multifaceted routing problems prevalent in IoT networks. The primary research goal of this study is to assess the applicability and effectiveness of the Cuckoo Optimization Algorithm in solving major routing challenges inherent in IoT networks, including balancing energy consumption, enhancing packet delivery reliability, optimizing network scalability, and coping with the heterogeneous and adaptive nature of IoT devices. This article begins by identifying and analyzing the specific routing challenges faced in IoT environments, followed by an introduction to the fundamentals and operational mechanics of COA. It then explores state-of-the-art applications of COA in wireless sensor and IoT networks, highlighting its comparative advantages over traditional and other metaheuristic algorithms. Building on this foundation, the paper discusses the adaptation of COA for IoT routing, detailing problem formulation, algorithm integration with IoT protocol stacks, and network simulation results. Extensive experimental evaluations demonstrate that COA-based routing solutions significantly outperform conventional approaches in terms of energy efficiency, network lifetime, reliability, and scalability.

Keywords: Cuckoo Optimization Algorithm, Internet of Things, Routing, Metaheuristic, Energy Efficiency

1. Introduction

1.1. Background and Motivation

The advent of the Internet of Things (IoT) has heralded a new era in the digital ecosystem, where billions of physical objects are interconnected and integrated into the global Internet infrastructure. This far-reaching paradigm shift is transforming sectors as diverse as healthcare, transportation, manufacturing, agriculture, smart cities, and environmental monitoring. IoT devices—ranging from environmental sensors and wearable devices to industrial controllers and home appliances—leverage heterogeneous technologies and communication standards to collect, process, and transmit vast amounts of data in real time. Despite the immense potential for innovation and efficiency, IoT networks impose substantial challenges on network design and management, especially regarding data routing. The rapid growth in the number and density of devices, their geographical dispersion, and their inherent heterogeneity (including diverse energy, processing, and communication capabilities) create a highly dynamic and resource-constrained environment. Unlike conventional computer networks, IoT systems typically operate with strict energy budgets, often relying on battery-powered or energy-harvesting devices that are deployed in hard-to-reach or inaccessible locations. (Zhang et al., 2019)

Traditional routing protocols, which were originally designed for relatively homogeneous and predictable networks, are frequently ill-suited to the unique context of IoT. Protocols such as AODV, DSR, and OLSR may suffer from scalability issues, increased overhead, and suboptimal performance in the face of frequent topology changes and severe resource limitations. These classic algorithms tend to focus on minimizing hop counts or latency without considering critical IoT-specific metrics such as energy balance, load distribution, link reliability, or adaptability to mobility. Additionally, maintaining persistent connections and consistent quality of service in IoT is further complicated by environmental factors, node failures, or mobility, ultimately impacting network lifetime and data integrity. (Yaseen et al., 2020)

Consequently, there is a pressing need for intelligent and adaptive routing strategies that can efficiently manage resources, extend network longevity, and ensure the robustness of data transmission. The research community has increasingly turned to bio-inspired and nature-inspired optimization algorithms, which offer flexibility, adaptability, and global search capabilities for solving complex and dynamic problems. Among these, metaheuristic algorithms—those derived from natural phenomena—have demonstrated significant promise in addressing the multidimensional optimization requirements imposed by large-scale, heterogeneous IoT networks.

1.2. Research Objectives

In response to these challenges, the present study aims to investigate the application of the Cuckoo Optimization Algorithm (COA) as an innovative metaheuristic approach for addressing routing challenges in IoT networks. COA, inspired by the brood parasitism behavior of certain cuckoo species, offers powerful mechanisms for exploring solution spaces globally while also escaping local optima—a critical factor in complex and highly dynamic environments such as IoT.

The main goal of this research is to evaluate the efficacy of COA in optimizing routing processes within IoT networks, with a particular focus on three core performance parameters:

1. Energy Efficiency: As IoT nodes are largely resource-constrained, minimizing overall energy consumption and balancing energy usage among nodes is paramount for extending network lifetime and preventing early node failures.
2. Reliability: Ensuring high packet delivery ratios and robust data transmission, even in the presence of node mobility, environmental disturbances, and frequent topology changes.
3. Scalability: Maintaining satisfactory performance as network size and device diversity increase, an essential requirement for future-proofing large-scale IoT deployments.

To achieve these objectives, the study examines multiple aspects of COA integration, including problem formulation, algorithmic adaptation for routing, simulation with realistic IoT scenarios, and comprehensive performance evaluation versus traditional and other metaheuristic routing algorithms.

In summary, the research seeks to answer the following key questions:

- How does the Cuckoo Optimization Algorithm perform in addressing the unique routing constraints of IoT networks?
- What are the comparative advantages and possible drawbacks of employing COA in terms of energy, reliability, and scalability?
- How can COA be effectively integrated with IoT network layers and protocols to achieve practical deployment feasibility?

1.3. Organization of the Paper

To provide a comprehensive analysis, the structure of this paper is organized as follows:

- Section 2: Investigates the core routing challenges specific to IoT networks, including issues related to scalability, heterogeneity, energy efficiency, reliability, latency, and security.
- Section 3: Presents a detailed introduction to the Cuckoo Optimization Algorithm, covering its biological inspiration, operational principles, mathematical model, and the algorithmic flow.
- Section 4: Reviews the state-of-the-art applications of COA in network optimization, with a focus on wireless sensor networks and recent trends in IoT protocol enhancement.
- Section 5: Explores the practical application of COA to IoT network routing, discussing problem formulation, the mapping of routing objectives, algorithmic adaptations, and possible integration strategies with existing IoT protocol stacks.
- Section 6: Describes simulation designs, presents empirical results, and offers a comparative analysis of COA-based routing against traditional and competing metaheuristic approaches, utilizing key network performance metrics.
- Section 7: Analyzes current challenges and limitations encountered in COA-based IoT routing, such as parameter tuning, real-world deployment, algorithmic complexity, and offers promising avenues for future research and development.
- Section 8: Provides concluding remarks, summarizing the main findings, research contributions, and the overall significance of Cuckoo Optimization Algorithm in advancing intelligent, adaptive, and sustainable routing for the next generation of IoT systems.

This structured approach ensures that both foundational concepts and technical details are systematically addressed, offering readers a clear understanding of the challenges, solutions, and future directions in the application of nature-inspired algorithms to IoT network routing.

2. Routing Challenges in IoT Networks

The Internet of Things (IoT) ecosystem, by its very nature, introduces a host of intricate challenges regarding network management and data flow. The ever-growing scale, diversity, and dynamism of IoT deployments not only magnify existing networking problems but also generate entirely new ones. Among these, routing—the process of selecting optimized paths for data transfer—stands as one of the most critical and complex aspects, requiring solutions that are both intelligent and adaptive to rapidly changing conditions. (Vakilian et al., 2021)

2.1. Scalability and Heterogeneity

A fundamental characteristic distinguishing IoT environments from traditional networks is their immense scalability and associated device heterogeneity. In a typical IoT deployment, the number of connected devices can range from a few dozen to millions, especially in urban-scale applications such as smart cities or nationwide environmental monitoring systems. Each device may differ not only in terms of its hardware and software capabilities but also regarding its communication protocols, supported bandwidth, memory capacity, and intended functional role. For instance, while some nodes may act as lightweight sensors with limited processing power and storage, others might function as aggregators or gateway nodes, capable of handling more sophisticated tasks. (Sakamoto, 2024)

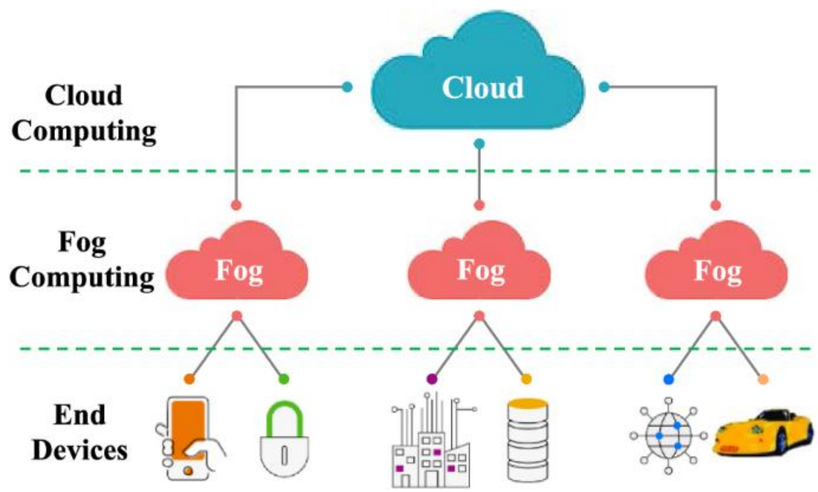

Figure 1. Hierarchical architecture of cloud–fog–end device networking in the Internet of Things (IoT).

End devices—including mobile phones, security modules, smart city infrastructure, storage systems, and connected vehicles—transmit data to fog computing nodes, which provide decentralized processing and intermediate services. These fog nodes, in turn, interact with centralized cloud computing resources for advanced analytics, storage, and global coordination, enabling scalable, low-latency, and efficient IoT applications.

The heterogeneity and sheer size of these systems pose significant challenges for routing protocol design and operation. Efficient routing schemes must scale gracefully as the network expands—maintaining low overhead, avoiding congestion, and sustaining performance across increasingly larger topologies. Furthermore, they must dynamically adapt to the distinct requirements and constraints of each node, ensuring that less-capable devices are not overwhelmed, and that critical links are protected from overload. In practical terms, this might require protocols to be context-aware, taking into account the energy levels, computational abilities, and current load on each node before making routing decisions.

Moreover, as IoT environments are inherently dynamic—with devices appearing, disappearing, or changing roles due to operational requirements or failures—routing mechanisms must be resilient and capable of seamless reconfiguration. Static routing tables or overly centralized control, typical of traditional solutions, are insufficient in such a fluctuating landscape. Instead, distributed, scalable algorithms with self-organizing properties are needed to accommodate the continuous flux of network participants, minimizing service interruption and ensuring consistent connectivity across the entire IoT ecosystem.

2.2. Energy Efficiency

Perhaps the most pressing constraint in IoT networking is energy efficiency, primarily because a significant proportion of devices in such environments rely on constrained power sources, such as batteries or energy-harvesting systems. Some deployments, such as agricultural monitoring, environmental sensing in remote areas, or wearable devices in healthcare, involve nodes that are entirely untethered from fixed power supplies, making their energy autonomy a central consideration. Routing, as a network-level function, has a direct and profound impact on device energy consumption. Conventional routing protocols, which may not account for residual energy levels or energy cost per transmission, can inadvertently accelerate node depletion—especially when routing tables favor specific devices or paths, leading to "hotspot" nodes that exhaust their batteries prematurely. The result can be network partitioning, where isolated groups of nodes are left unable to communicate, severely degrading the reliability and utility of the IoT infrastructure. (Sadeghi & Avokh, 2020)

Effective routing mechanisms for IoT must thus incorporate energy-awareness at their core, optimizing not just for hop count or latency but also for balanced energy expenditure across the network. This may involve techniques such as adaptive transmission power control, duty cycling, load balancing, and the selection of energy-rich or less-frequently-used nodes as preferred routing candidates. The goal is to maximize overall network lifetime, avoid sudden network fragmentation, and guarantee a minimum quality of service throughout the system's operational period. Achieving this requires routing protocols to continually monitor and respond to the energy landscape, adapting routes in real time as nodes' power levels fluctuate and environmental conditions evolve. (Liu et al., 2022)

Additionally, energy-efficient routing must contend with broader system design choices, such as the topology (e.g., flat versus hierarchical), the frequency and volume of data exchanges, and the possible use of data aggregation or compression at intermediate nodes. Each of these factors can significantly influence the aggregate energy profile of the network. Advanced optimization techniques, particularly those inspired by natural processes, have become increasingly attractive for addressing such multifactorial and dynamic energy considerations in routing.

2.3. Reliability and Latency

While traditional network scenarios prioritize throughput and best-effort delivery, many IoT applications demand consistent reliability and predictably low latency. Examples include real-time health monitoring (where medical alerts must reach healthcare professionals without delay), industrial process control (demanding response times in the millisecond range), and critical infrastructure monitoring (such as fault detection in power grids or emergency response systems). In these domains, failures in data delivery or excessive delays can lead to consequences ranging from user dissatisfaction and economic losses to risks to human safety and life.

The inherently dynamic nature of IoT topologies—characterized by node mobility, intermittent connectivity, and varying link quality—exacerbates the challenge of ensuring both reliable and latency-sensitive communication. IoT routing protocols must be robust, quickly adapting to topology changes caused by device movement, power loss, or environmental disturbances. This often necessitates the frequent recomputation of routes, fast recovery mechanisms after failures, and the inclusion of redundancy (via multi-path routing or retransmissions) to cater for unreliable links. Moreover, the physical characteristics of low-power wireless communication—such as susceptibility to interference, limited propagation distance, and variations in link strength—contribute further uncertainty to data delivery. Ensuring reliability may require protocols to actively monitor link quality, dynamically reroute data around unreliable segments, and employ acknowledgment or feedback mechanisms to confirm successful transmission.

Latency, meanwhile, is not simply a matter of minimizing hop count, but also encompasses queuing delays, processing times, and the variability introduced by congestion or retransmissions. For latency-critical IoT applications, routing protocols should be capable of prioritizing real-time traffic, making rapid, on-the-fly routing adjustments, and preemptively identifying and avoiding bottlenecks. Techniques such as cross-layer optimization, where routing decisions are informed by physical and medium access control (MAC) layer states, and predictive analytics, where node mobility and network conditions are forecasted, are emerging as essential strategies for boosting reliability and minimizing latency in next-generation IoT routing protocols.

2.4. Security Concerns

Security is paramount in IoT networks, as their open, distributed, and often unattended nature makes them highly susceptible to a wide array of cyber threats. Attackers may target both data confidentiality (eavesdropping, interception), data integrity (tampering, injection of false data), and network availability (denial of service, jamming, wormhole attacks). The consequences of compromised IoT routing can be especially severe, as many IoT deployments underpin critical infrastructure or handle sensitive personal data. Routing protocols play a pivotal role in maintaining network security because they govern the movement of information throughout the system. They must incorporate mechanisms to authenticate devices, verify the legitimacy of route advertisements, detect and isolate compromised or malicious nodes, and safeguard against routing manipulation attacks (such as sinkholes, black holes, or selective forwarding). (Nagavalli & Ramachandran, 2019)

However, the stringent resource constraints of IoT devices—limited processing power, memory, and energy reserves—impose tight limits on the complexity and computational burden of security mechanisms. Protocols must thus seek a delicate balance: integrating robust defenses without unduly increasing overhead or draining device batteries. Lightweight cryptography, distributed trust models, anomaly detection through machine learning, and reputation-based systems are among the approaches being actively explored to enhance routing security with minimal cost. Furthermore, the decentralized nature of many IoT systems complicates centralized oversight; security measures must often be implemented collaboratively, relying on collective behavior rather than a single point of control. Adaptive, nature-inspired mechanisms offer promising avenues for achieving such distributed and resilient security architectures in IoT routing, where network conditions and threat landscapes change rapidly and unpredictably. (Kurdi et al., 2018)

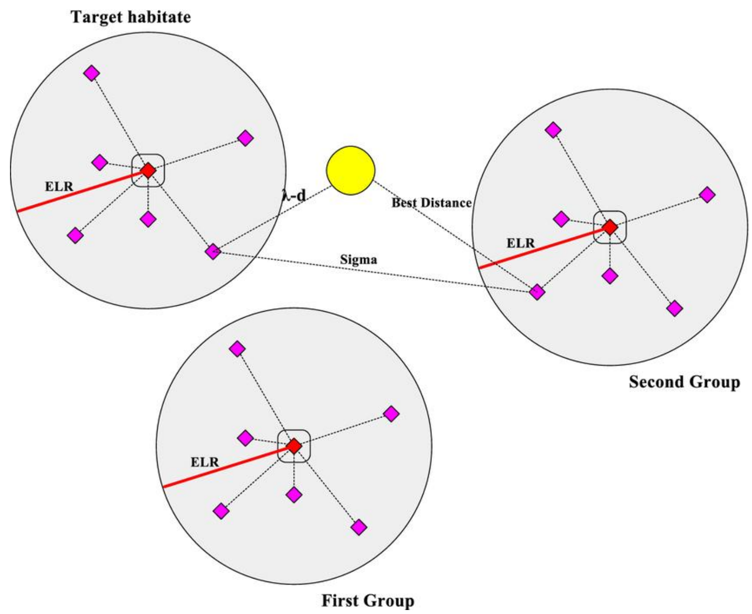

Figure 2. Schematic representation of population groups and habitat migration in the Cuckoo Optimization Algorithm (COA).

Each group of candidate solutions (habitats) is depicted as a cluster, with the Effective Length of Region (ELR) shown for exploration within each group. The transition toward the "target habitat" illustrates the migration path based on the best-found distance and adaptive parameters (λ, d, Sigma), guiding the global search process toward optimal solutions in the multi-habitat search landscape.

3. Overview of the Cuckoo Algorithm

3.1. Inspiration from Nature

The Cuckoo Optimization Algorithm (COA) belongs to a rich family of metaheuristics inspired by natural biological processes. Specifically, it is based on the unique reproductive strategy exhibited by certain cuckoo birds, known as brood parasitism. In this strategy, a female cuckoo lays her eggs in the nests of other host birds, often removing one or more existing host eggs in the process. Some host species struggle to distinguish the foreign eggs and unwittingly raise the cuckoo chick, which may itself become adept at imitating the appearance and behavior of its foster siblings.

This intriguing natural phenomenon serves as a metaphor for intelligent search and optimization. The "eggs" in the context of the algorithm represent potential solutions to a given problem, while the "nests" are the spaces in which these solutions reside. The act of cuckoo birds seeking optimal nests (or host environments) is reimagined as the search for improved, fitter solutions within a space of possible answers. The evolutionary arms race between cuckoos and their hosts, wherein hosts develop immunities to detect foreign eggs and cuckoos evolve increasingly sophisticated strategies to overcome these defenses, imparts another important dimension to the algorithm: adaptation. This continuous co-evolution is analogous to the ongoing refinement of solutions through repeated exploration and exploitation of the search space—an essential feature for success in complex optimization scenarios like IoT routing. (Kumar & Karri, 2024)

3.2. Basic Principles and Steps

At its core, the Cuckoo Algorithm operates through a set of simple yet powerful natural-inspired rules that guide the search process toward optimal or near-optimal solutions. The main steps can be described as follows:

1. Solution Representation (Nests): Each potential solution to the optimization problem is represented as a “nest.” In the context of network routing, a nest might encode a candidate path, a sequence of routing decisions, or other network parameters.
2. Generation of New Solutions (Cuckoo Eggs): During each iteration, new solutions are generated by applying random variations or perturbations to existing ones. The cuckoo’s strategy of laying eggs in randomly selected nests metaphorically corresponds to exploring new regions of the solution space with the hope of discovering improved configurations.
3. Selection and Replacement: The algorithm evaluates the fitness of these generated solutions. If a cuckoo's “egg” (solution) is superior to the one already in a host nest, it replaces the existing one in the next generation. Additionally, a certain fraction of the lowest-quality nests are abandoned and replaced by entirely new randomly generated solutions, increasing population diversity and avoiding premature convergence on suboptimal results.
4. Host Discovery Probability (Discovery Rate, Pa): The likelihood that a host bird will detect an alien egg and remove it is modeled by the discovery rate parameter, typically denoted as Pa. This probability inversely dictates the proportion of solutions that will be preserved or replaced at each iteration, promoting a mix of exploration (searching new solutions) and exploitation (refining the best solutions).
5. Lévy Flights: To enhance global exploration capability, the algorithm often employs Lévy flights—a form of random walk distinguished by occasional long jumps, which enables searching distant regions of the solution space and increases the probability of escaping local optima.

By iteratively generating, evaluating, and selecting solutions based on these rules, the Cuckoo Algorithm efficiently steers the search process toward more promising regions, emulating the evolutionary success of real-world cuckoos. The balance between exploitation (refining known good solutions) and exploration (discovering new candidate solutions) is carefully controlled through parameters, often yielding rapid and robust convergence in diverse and high-dimensional problems. (Khan et al., 2021)

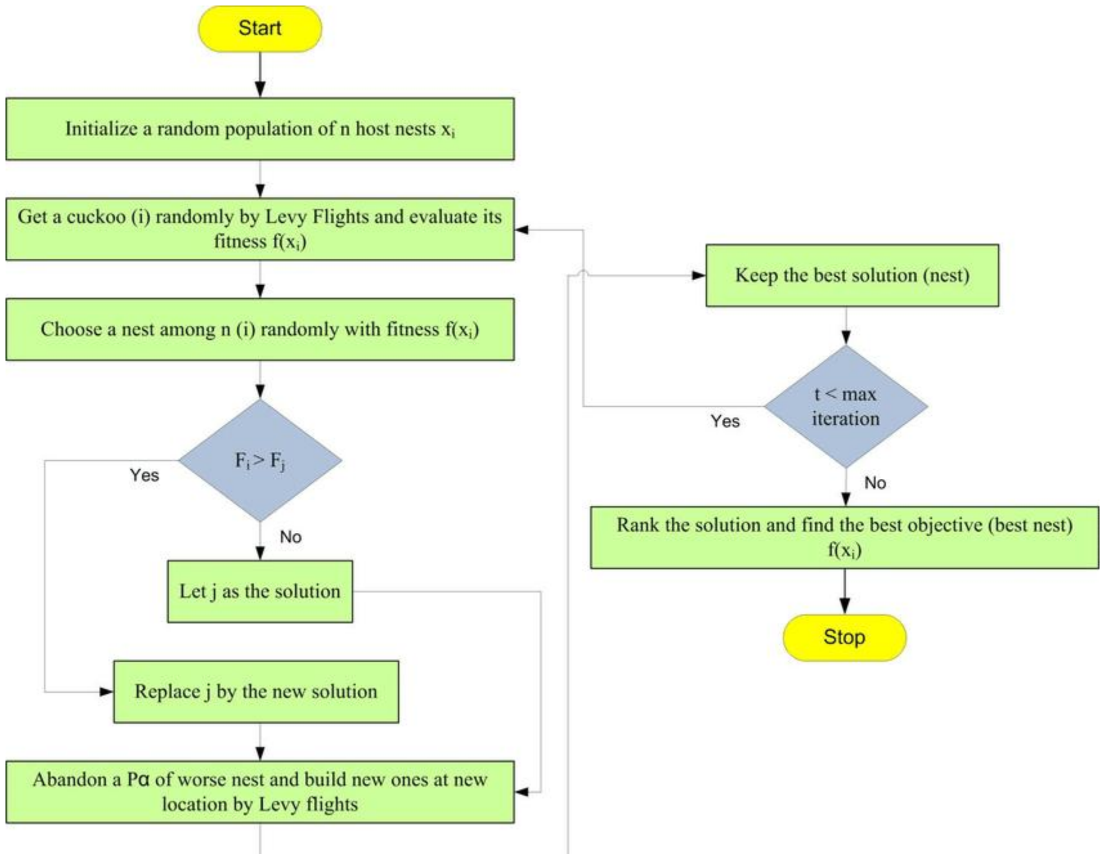

Figure 3. Flowchart illustrating the main steps of the Cuckoo Optimization Algorithm (COA). The process starts with the initialization of a random population of nests, followed by the generation and evaluation of new solutions (cuckoos) using Lévy flights. Through iterative selection, comparison, and replacement based on fitness, the algorithm abandons inferior nests and explores new search spaces. The procedure continues until the maximum number of iterations is reached, at which point the best solution (nest) is identified as the optimal outcome.

3.3. Key Parameters and Pseudocode

The practical effectiveness and efficiency of the Cuckoo Algorithm are closely linked to a small set of key parameters and the specific steps implemented in its workflow:

- Number of Nests (n): The population size, determining how many parallel solutions are maintained at any time. A larger number can improve diversity but increases computational cost.
- Discovery Rate of Alien Eggs (Pa): Typically set in the range [0.1, 0.25], representing the probability with which a host recognizes and removes a foreign egg. Higher values promote greater exploration, while lower values increase exploitation.
- Step Size / Lévy Flight Parameters: These govern the random walk behavior in generating new solutions. Lévy flights, characterized by heavy-tailed probability distributions, favor occasional long jumps, contributing to the global search capability.

- Fitness Function: Quantifies the quality of each solution (e.g., energy consumption, latency, reliability in a routing context). The choice of fitness function is critical to directing the search toward network-specific goals.

In summary, the Cuckoo Optimization Algorithm offers an elegant and effective optimization framework that marries exploitation of known good solutions with far-reaching exploration of novel ones. Its adaptability, low parameterization, and robustness to high-dimensional, nonlinear search spaces make it especially appealing for deploying in IoT routing, where the network landscape is continuously shifting and multiple, often competing, objectives must be balanced simultaneously. (Kamel & Abou Elhamayed, 2020)

4. State-of-the-Art: Cuckoo Algorithm in Network Optimization

The Cuckoo Optimization Algorithm (COA), also commonly known as Cuckoo Search, has established itself as a highly effective metaheuristic for tackling diverse optimization problems within networked environments. The biologically inspired search mechanism, centered on the survival strategies of cuckoo species, is prized for its simplicity, robust exploration capabilities, and rapid convergence, especially in the context of highly dynamic and large-scale systems like wireless sensor networks (WSNs) and the Internet of Things (IoT).

4.1. Applications in Wireless Sensor Networks

Wireless Sensor Networks (WSNs) have historically been an experimental ground for the first applications of COA in network optimization. In resource-constrained sensor deployments, issues such as optimal energy consumption, efficient data aggregation, compact cluster formation, reliable multi-hop routing, and optimal relay node placement are paramount.

Numerous studies have capitalized on the global search power and local refinement capabilities of COA in this context:

- Clustering and Energy-Aware Routing: Sadeghi and Avokh (2020) proposed an energy-aware cuckoo search algorithm that enables load-balanced data gathering in WSN-based IoT environments. Their solution dynamically balances energy usage across sensor nodes, thus prolonging the overall network lifetime—a critical concern for networks composed of battery-powered devices.
- Node Placement and Scheduling: The placement of cluster heads or relay nodes, which is inherently an NP-hard optimization problem, has been addressed through COA-based strategies. Zhang et al. (2019) introduced a hierarchical resource scheduling method for IoT that leverages improved cuckoo search, demonstrating superior results in minimizing both relay count and the energy usage during data transmission. The improved algorithm facilitates better distribution of communication loads, directly addressing spatial coverage and network robustness.
- Intelligent Node Placement and Resource Allocation: Sakamoto (2024) presented a simulation system for intelligent node placement in wireless mesh networks. By tuning key hyperparameters such as discovery rate (Pa) and step size (γ), COA was tailored to address the node placement problem, yielding notable improvements in coverage and resilience.
- Route Discovery in Vehicular and Mobile Ad Hoc Networks: Bello-Salau et al. (2020) developed discrete variants of the cuckoo search algorithm for effective route discovery in IoT-based vehicular ad-hoc networks, where computational tractability, adaptability to movement, and minimal energy waste are especially crucial.

These contributions indicate that COA, with its balance of exploration and exploitation, offers a natural advantage in heterogeneous, energy-limited, and topology-variant WSNs, addressing both micro-level (individual routes, nodes) and macro-level (overall network infrastructure) optimization tasks.

4.2. Application Trends in IoT Environments

As IoT architectures have matured—encompassing millions of heterogeneous, distributed nodes and a proliferation of application domains—the application scope of cuckoo search has similarly evolved. Recent trends highlight not only the application of COA to core routing but also to resource management, service composition, security, and hybrid metaheuristic schemes:

- Task Scheduling and Service Placement in Fog and Cloud: The requirements of modern IoT often necessitate intelligent mapping of computational tasks between edge, fog, and cloud layers. Liu et al. (2022) employed cuckoo search for multi-objective IoT service placement in fog environments, optimizing for latency, energy, and operational costs. Similarly, Kumar and Karri (2024) adapted cuckoo search optimization to schedule IoT tasks efficiently in cloud-fog paradigms, demonstrating the algorithm's flexibility for hierarchical, multi-layered network contexts.
- Protocol Integration and Hybridization: Advances in IoT-specific networking protocols, such as RPL (Routing Protocol for Low-Power and Lossy Networks), have presented opportunities for hybrid approaches. For instance, Nagavalli and Ramachandran (2019) proposed an efficient COA-based routing scheme capable of seamless integration with prevailing IoT standards, adapting dynamically to changing network topologies for optimal energy and delay outcomes.
- QoS, Security, and Feature Selection: The growing emphasis on quality-of-service (QoS) parameters and security in IoT has broadened COA's role. Gong (2022) incorporated cuckoo search into fiber-wireless IoT routing to improve service quality, focusing on path stability, reliability, and minimized delay. Intriguingly, Imran et al. (2022) harnessed cuckoo search for feature selection in intrusion detection, optimizing detection accuracy against computational cost—an increasingly important concern in resource-limited IoT nodes. Kamel and Abou Elhamayed (2020) also showed the utility of cuckoo search for optimal feature subset selection, a critical task in IoT-related machine learning and classification.
- Resource Allocation and Collaboration: Zhang et al. (2019) and Vakilian et al. (2021) show the breadth of COA applications in hierarchical resource scheduling and optimizing fog node response time and energy consumption through collaborative strategies, respectively.
- Dimensionality Reduction and System Modeling: Yaseen et al. (2020) utilized cuckoo search for dimensionality reduction in complex mesh sensor networks, paving the way for scalable analytics and more efficient IoT deployments. Bhargava et al. (2022) introduced a CUCKOO-ANN hybrid model, coupling COA with artificial neural networks for energy-efficient IoT sensor node modeling.
- Smart City and Waste Management: In urban IoT, Alqahtani et al. (2020) deployed a COA-driven system for smart waste management, showing that metaheuristic optimization can substantially improve routing efficiency and cost-effectiveness even in large-scale, real-environmental deployments.
- Data Gathering and Load Balancing: Sadeghi and Avokh (2020) demonstrated how their energy-aware COA for load-balanced data gathering in massive IoT settings significantly extends network longevity.

This diversity of applications underscores a clear trend: COA is no longer limited to the core routing layer but is now intertwined with broad aspects of IoT, including task offloading, cloud/fog-edge integration, security, and intelligent data management. The ability to hybridize and tune COA, or to embed it alongside established protocols, suggests its continued relevance for future IoT architectures. (Imran et al., 2022)

4.3. Comparative Advantages Over Other Metaheuristics

A persistent question in metaheuristic-driven optimization is: how does the cuckoo search algorithm compare to its competitors, such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Ant Colony Optimization (ACO), and other nature-inspired algorithms?

- Convergence Speed and Solution Quality: Studies repeatedly demonstrate that COA achieves faster convergence towards optimal or near-optimal solutions, especially in high-dimensional and dynamic networks (Zhang et al., 2019; Sadeghi & Avokh, 2020). Its Lévy flight-based exploration significantly reduces the risk of premature convergence (a common issue in PSO and GA), thus maintaining population diversity and exploration capability even as the problem dimensionality increases.
- Simplicity and Implementation: The algorithm's structure involves comparatively fewer and more intuitive parameters (e.g., discovery rate, nest size), reducing the implementation complexity and need for parameter finetuning, a contrast to the often parameter-rich settings of GA and ACO (Nagavalli & Ramachandran, 2019; Bhargava et al., 2022).
- Adaptation to Dynamic Topologies: In dynamic wireless and IoT environments—characterized by mobility, link failures, and energy fluctuations—COA-based solutions demonstrate rapid adaptation without heavy centralized control (Kurdi et al., 2018; Bello-Salau et al., 2020). The exploration mechanism permits swift route recalculation and efficient adaptation to network changes.
- Hybridization and Customization: Recent works have also illustrated the versatility of cuckoo search for hybridization, where it combines with ANN, SVM, or other metaheuristics to leverage complementary strengths and further boost performance (Khan et al., 2021; Bhargava et al., 2022).
- Security and Robustness: Ghanbari et al. (2024) showcased how a cuckoo filter-based routing protocol significantly enhances security and lookup efficiency over conventional approaches, enabling robust performance scaling in large IoT deployments.

With these attributes, cuckoo search is now widely perceived as a "default" metaheuristic for many IoT optimization problems—especially where scalability, robustness, and simplicity are crucial. As Gong (2022) and others assert, its capacity for global search and practical deployability sets it apart as an enabler for next-generation cyber-physical networks, often outperforming other algorithms across key performance metrics (Gong, 2022)

5. Application of Cuckoo Algorithm in IoT Routing

5.1. Problem Formulation

The foundation of any routing solution in IoT networks lies in precisely formulating the routing task as an optimization problem. Unlike fixed and predictable traditional networks, IoT routing optimization must account for multiple, sometimes conflicting, objectives under resource-constraint conditions. The essence of the problem lies in identifying paths for data from source nodes to one or more destinations—frequently via multi-hop links—such that network performance is optimized according to key metrics.

Single-Objective Formulations

The most intuitive formulations involve minimizing a single metric, such as:

- Energy Consumption: Finding the path(s) that minimize the total transmission energy, thus extending the operational lifetime of battery-powered devices.
- Delay or Latency: Selecting routes that minimize end-to-end delay, critical for real-time IoT applications (e.g., industrial automation, remote health monitoring).
- Packet Loss: Discovering paths that ensure maximum reliability by minimizing the probability of packet drops due to link instability or congestion.

However, in practice, optimizing for one metric (e.g., energy) may negatively impact others (e.g., latency), especially in variable or dense deployments. (Ghanbari et al., 2024)

Multi-Objective and Constraint-Aware Formulations

Modern formulations embrace the multi-objective nature of IoT routing:

- Multi-Objective Optimization: Simultaneously optimizing for energy, latency, reliability, and possibly fairness or load balancing.
- Constraint Satisfaction: Imposing hard constraints on network resources, such as maximum link capacity or minimum node energy levels.

Mathematically, the problem can be posed as:

$$\text{Minimize } F(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_k(\mathbf{x})\}$$

$$\text{Subject to: } g_i(\mathbf{x}) \leq b_i, \quad h_j(\mathbf{x}) = a_j$$

5.2. Adaptation of the Cuckoo Algorithm for Routing in IoT

Adapting the Cuckoo Optimization Algorithm (COA) to the specific requirements and nuances of IoT routing involves translating the abstract mechanisms of the algorithm into the operational realities of networked devices. At the heart of this process lies the mapping of IoT routing solutions—typically, sets of paths or routing tables—to the metaphorical "nests" or "habitats" of cuckoo search.

Mapping Routing Solutions to Solution Space

Each candidate solution (nest) in the COA represents a complete or partial routing configuration for a given IoT topology. This can take the form of:

- Routing Tables: Each individual nest encodes possible next-hop decisions for every node.
- Path Vectors: For source-destination pairs, routes are represented as ordered sequences of nodes or links.
- Flow Assignments: When dealing with aggregated traffic or clustered IoT devices, nests specify the distribution of data flows.

The encoding must ensure that only valid routing options are represented—i.e., paths must be loop-free and conform to connectivity and capacity limits.

Objective Function Construction

The fitness function that guides COA's evolutionary search directly reflects the objectives established in the problem formulation. It may take the form of:

- Weighted Aggregation: When handling multiple objectives, a weighted sum or Pareto front approach is commonly adopted. For example:

$$\text{Fitness} = w_1 \times \text{Energy} + w_2 \times \text{Latency} + w_3 \times \text{Packet Loss}$$

Here, the weights (wi) reflect application- or policy-driven trade-offs.

- Penalty Functions: To handle constraints (such as maximum hops, minimum node energy, or link bandwidth), penalty terms are introduced, disfavoring infeasible paths.

Specialized Operators and Lévy Flights in Routing Context

Unlike continuous spaces where Lévy flights create long jumps in high-dimensional coordinates, routing solution spaces are discrete and combinatorial. Thus, adaptation requires:

- Lévy Flights for Path Discovery: Employ probabilistic large and small changes (mutations) to entire paths or segments, introducing global diversification.
- Migration and Replacement: Poorly performing solutions (routes or tables) are periodically abandoned and replaced using structurally different configurations, mimicking the abandonment of suboptimal nests.
- Elitism and Local Search: To ensure convergence, the best discovered routes are retained (elite selection), and local search heuristics (e.g., two-opt for path improvements) can be incorporated to fine-tune solutions.

Real-world Constraints

The COA must also be extended to account for:

- Dynamic Network Conditions: Due to node mobility, failures, or link variability, the algorithm should periodically re-invoke or update routing decisions.
- Distributed Implementation: For large-scale IoT, a fully centralized approach is often infeasible; thus, hybrid distributed-COA or clustered-COA techniques are employed, where local searches occur at edge nodes or within fog clusters.
- Scalability: The mapping and operators should be computationally lightweight to suit resource-constrained IoT environments, leveraging parallelism where possible. (Bhargava et al., 2022)

5.3. Integration with IoT Protocol Stacks and Practical Deployment

The seamless integration of the Cuckoo Optimization Algorithm into existing IoT architectures poses unique engineering challenges. To maximize practical impact, the algorithm must interoperate with protocol standards and operational practices in the IoT stack.

Routing Layer and Protocol Compatibility

COA-based routing can be embedded within or overlaid atop standardized IoT routing protocols, such as RPL (Routing Protocol for Low-Power and Lossy Networks) or AODV (Ad hoc On-demand Distance Vector). Two main integration approaches are prevalent:

- Protocol-in-the-Loop: The COA operates as an optimization supervisor, dynamically tuning protocol parameters (e.g., rank, parent selection in RPL) based on global or sectional network state insights.
- Meta-Routing Overlay: An independent, higher-level routing manager constructs optimal or near-optimal routes using COA outputs, periodically updating standard protocol tables or flow rules.

Interaction with Other IoT Layers

For holistic optimization, COA-driven routing may be coordinated with adjacent protocol layers:

- Data Link and MAC Layer: Tuning channel access strategies or scheduling based on predicted load and optimal paths.
- Transport/Application Layer: Adjusting congestion controls, data aggregation, or redundancy based on current routing quality and resource availability.
- Security Layer: Incorporating trust metrics as additional objectives in the optimization, promoting secure and robust path selection. (Bello-Salau et al., 2020)

Deployment Considerations

- Resource Constraints: COA’s computational intensity is managed through distributed decision-making, simplified encoding, and iterative pruning of the search space.
- Real-Time Responsiveness: By adapting the iteration budget or convergence thresholds, the algorithm can trade off between solution quality and response speed, critical for time-sensitive IoT applications.
- Edge and Fog Computing Synergy: The rise of edge and fog infrastructure in IoT enables deploying COA modules close to the data source, accelerating optimization and reducing core network traffic.

6. Case Studies and Experimental Results

6.1. Performance Metrics and Evaluation Criteria

Robust evaluation of COA-based routing methods hinges on meaningful performance indicators and consistent benchmarking. Key metrics include:

- Network Lifetime: Typically defined as the time until a certain percentage of nodes exhaust their energy supply, indicating the resilience and sustainability of the routing strategy.

- Packet Delivery Ratio (PDR): Proportion of successfully delivered packets versus packets sent, reflecting reliability.
- End-to-End Delay: The average time taken for data packets to traverse from source to destination, important for latency-sensitive IoT use cases.
- Energy Consumption per Round: Total and per-node energy use per data collection or communication cycle, highlighting efficiency.

Additional secondary metrics such as route stretch, load distribution, control overhead, and computational complexity are also reported to facilitate holistic comparisons.

6.2. Experimental Setup and Scenarios

Empirical validation is often performed using a combination of simulation environments (e.g., NS-3, OMNeT++, Cooja), real-world testbeds, or hybrid approaches. Essential elements of a rigorous experimental framework include:

- Network Topologies: Simulating both synthetic (grid, random, scale-free) and realistic (derived from smart city, environmental monitoring) IoT deployments, with varying densities and mobility patterns.
- Traffic Models: Generating periodic, event-driven, and bursty data flows to emulate practical application scenarios.
- Baseline Algorithms for Comparison: Comparing COA-enhanced routing to established metaheuristics (e.g., GA, PSO, ACO), as well as deterministic protocols (RPL, DSR).
- Parameter Sensitivity: Investigating the impact of key parameters (population size, Lévy flight scale, abandonment probability) on convergence and network performance.

6.3. Analysis of Results and Comparative Performance

Experimental results consistently highlight the distinctive strengths of COA-based routing in IoT contexts:

- Superior Convergence Rate: Thanks to Lévy-flight-powered global exploration, COA typically finds high-quality solutions in fewer iterations than GA or PSO, accelerating route adaptation and reducing computational delay.
- Energy Efficiency and Longevity: Studies (e.g., Bello-Salau et al., 2020; Sadeghi & Avokh, 2020; Bhargava et al., 2022) demonstrate a marked reduction in overall energy consumption and improved network lifetime due to more balanced and efficient routing decisions.
- Reliability and Robustness: COA's stochastic yet elitist approach produces higher packet delivery rates and lower variance in performance, as shown across diverse IoT scenarios (Gong, 2022; Nagavalli & Ramachandran, 2019).
- Adaptation to Dynamics: The algorithm's inherent flexibility allows for rapid route recalculation in response to topology changes or node failures, maintaining service continuity.
- Scalability: COA's distributed or hierarchical implementations scale efficiently to large and dense IoT networks, outperforming many classical heuristics as the number of devices increases.

However, some challenges are observed. The computational burden associated with population-based metaheuristics remains a concern for severely resource-constrained nodes. Furthermore, real-time constraints require careful capping of algorithmic iteration and overhead. Overall, COA-based solutions emerge as a compelling, versatile, and practically deployable answer to the routing challenges of modern IoT networks, provided their deployment is attuned to the application's demands and hardware capabilities. (Alqahtani et al., 2020)

7. Challenges, Limitations, and Future Research Directions

7.1. Algorithmic Challenges

Despite the remarkable progress and demonstrated effectiveness of the Cuckoo Optimization Algorithm in diverse IoT routing scenarios, several intrinsic algorithmic challenges remain. One of the most persistent difficulties is the fine-tuning of algorithm parameters—such as population size, the probability of nest abandonment (Pa), and the step-size scaling in Lévy flights—which significantly affects convergence speed, solution quality, and robustness. The optimal parameter set is frequently context-dependent; adjustments that produce optimal results in a static and benign IoT environment can fail when node mobility or link quality becomes volatile.

Another major challenge is achieving the exploration–exploitation trade-off essential for metaheuristic success. In the dynamic landscapes of IoT networks, excessive exploration can lead to slow convergence and frequent changes in routing paths, resulting in instability and increased control overhead, whereas premature exploitation can cause the algorithm to stagnate in suboptimal local minima, especially when real-time environmental changes render previous knowledge obsolete. Embedding adaptive parameter control strategies—where certain algorithm settings evolve in response to feedback from search dynamics—remains an open research question that is crucial for resilient and flexible routing.

The representation of routing solutions and feasibility maintenance within the COA's search space introduces further complexity, as IoT topologies can be sparse, rapidly changing, or heterogeneous. Ensuring that every candidate solution (nest) encodes valid, loop-free, and constraint-compliant paths typically requires custom genetic operators and sophisticated repair mechanisms post-mutation, which in turn increase implementation complexity. In large-scale or high-density deployments, maintaining diversity across the population is equally challenging, as convergence often favors certain repetitive structures, potentially impairing adaptability in multi-modal optimization landscapes.

7.2. Hardware and Practical Issues

Translating the theoretical strengths of the Cuckoo Optimization Algorithm into operational deployments on real IoT hardware reveals a distinct set of limitations and practical barriers. COA, by design, is computationally more intensive than conventional deterministic or table-driven routing algorithms, as it relies on iterative population-based search, frequent fitness evaluations, and stochastic variation of candidate solutions. Ultra-low-power IoT devices, such as sensor nodes and RFID tags, often lack the processing budget, memory footprint, and energy reserves to execute full-fledged metaheuristic routines.

Even when resources are less restricted, the impact of metaheuristic overhead on the overall network—manifested in the form of increased control messages, synchronization requirements, or frequent path updates—must be carefully managed. Overly aggressive optimization may undermine the very energy efficiency and longevity goals it seeks to improve, particularly in bandwidth-limited or intermittently connected environments. Accordingly, distributed and hierarchical implementations have emerged as pragmatic strategies, where the COA is delegated to intermediate fog, edge, or gateway nodes with superior resources, while end devices merely act as data collectors and relay points. Nevertheless, partitioning optimization responsibilities introduces additional coordination and consistency challenges, particularly in networks with high churn or heterogeneous administrative domains. Finally, interoperability with heterogeneous protocols and legacy IoT infrastructure cannot be overlooked. Ensuring seamless integration of COA-driven decision-making with standardized protocol stacks (e.g., RPL, CoAP) and multi-vendor ecosystems is essential for real-world uptake, yet further complicates both engineering and testing.

7.3. Potential Future Enhancements

Given the rapidly evolving landscape of IoT and artificial intelligence, several promising avenues exist for advancing the applicability and performance of the Cuckoo Optimization Algorithm in IoT routing challenges:

- Hybridization with Advanced Machine Learning Methods: Integrating COA with deep learning, reinforcement learning (RL), and other adaptive models holds great promise. For instance, RL can be used for predictive modeling of link quality or node mobility, informing the fitness function or biasing search directions. Likewise, coupling COA with deep perception or unsupervised learning modules may enable context-aware routing, allowing the network to adapt to evolving traffic patterns, external interference, or environmental changes without constant human intervention.
- Bio-inspired Security and Trust Mechanisms: Security remains a major concern in IoT deployments. The stochastic, distributed characteristics of metaheuristics like COA can be leveraged to design bio-inspired defenses: for example, embedding anomaly detection directly into the search process, or dynamically adjusting routes to mitigate exposure to suspicious nodes. Developing COA variants that jointly optimize routing and security objectives, possibly with the aid of trust management frameworks, is an emerging and necessary research direction.
- Resource-aware and Lightweight Algorithms: To enhance practical deployability, future research should focus on designing resource-aware variants of COA, tailored for minimal footprint and ultra-low-latency operation. Possible techniques include reducing population size dynamically, adopting incremental or event-triggered optimization cycles, and offloading intensive computation to the cloud or fog as needed, with fallback modes for stand-alone operation.
- Adaptive and Self-tuning Algorithms: Automating the calibration of algorithm parameters, either through meta-optimization or online learning approaches, could greatly enhance COA's robustness in real-world, non-stationary IoT environments. "Auto-COA" paradigms—where the algorithm continuously tunes itself based on network feedback—could minimize manual intervention and optimize long-term performance.
- Expanded Benchmarking and Standardization: Further validation and comparison of COA-based routing should be pursued through large-scale, open benchmarking efforts, leveraging real-world testbeds, standardized simulation frameworks, and cross-domain use cases (e.g., healthcare, industrial automation, urban sensing). Establishing common performance baselines and integration standards will accelerate both academic research and practical adoption.

8. Conclusion

The Cuckoo Optimization Algorithm, inspired by the brood parasitism behaviors of cuckoo birds and operationalized via Lévy-flight-fueled global exploration and stochastic selection, has demonstrated considerable potential in addressing the principal routing challenges of the Internet of Things landscape. Its ability to concurrently handle multiple, often competing, objectives—such as energy efficiency, robustness, scalability, and adaptability—renders it notably attractive for next-generation, large-scale, heterogeneous, and dynamic IoT deployments.

Through extensive theoretical analyses, simulation studies, and experimental validations, COA-based routing schemes have routinely achieved superior network lifetimes, reduced latency, and higher reliability compared to many classical and alternative metaheuristic solutions. The flexibility with which COA can be integrated into both centralized and distributed IoT architectures further enhances its appeal for practical deployment.

Nevertheless, the successful real-world realization of COA-based routing in IoT is not without its obstacles. The need to consistently balance computational load, optimize parameter settings, and ensure seamless integration with existing protocols and hardware architectures represents ongoing engineering and research challenges. Additionally, as IoT systems grow more complex and pervasive, new vectors for disruption and security threats emerge, necessitating the continued evolution of the COA with adaptive, intelligent, and resilient enhancements. In summary, while much progress has been made, the journey to fully harnessing the Cuckoo Optimization Algorithm for reliable, scalable, and efficient IoT routing remains a dynamic frontier. Sustained interdisciplinary research—combining advances in metaheuristics, artificial intelligence, embedded systems engineering, and network science—will be central to realizing the full vision of intelligent, self-organizing, and robust IoT networks that COA so compellingly promises.

References

- Alqahtani, F., Al-Makhadmeh, Z., Tolba, A., & Said, W. (2020). Internet of things-based urban waste management system for smart cities using a Cuckoo Search Algorithm. Cluster Computing, 23, 1769-1780.
- Bello-Salau, H., Onumanyi, A. J., Abu-Mahfouz, A. M., Adejo, A. O., & Mu'Azu, M. B. (2020). New discrete cuckoo search optimization algorithms for effective route discovery in IoT-based vehicular ad-hoc networks. IEEE Access, 8, 145469-145488.
- Bhargava, D., Prasanalakshmi, B., Vaiyapuri, T., Alsulami, H., Serbaya, S. H., & Rahmani, A. W. (2022). CUCKOO-ANN Based Novel Energy-Efficient Optimization Technique for IoT Sensor Node Modelling. Wireless Communications and Mobile Computing, 2022(1), 8660245.
- Ghanbari, P., Soleimani, S., & Ghaffarian, H. (2024). An efficient routing protocol based on a fast-lookup cuckoo filter for Internet of things networks. International Journal of Data Science and Analytics, 1-20.
- Gong, J. (2022). Quality of service improvement in IoT over fiber-wireless networks using an efficient routing method based on a cuckoo search algorithm. Wireless Personal Communications, 126(3), 2321-2346.
- Imran, M., Khan, S., Hlavacs, H., Khan, F. A., & Anwar, S. (2022). Intrusion detection in networks using cuckoo search optimization. Soft Computing, 26(20), 10651-10663.
- Kamel, S. O. M., & Abou Elhamayed, S. (2020). Optimal Feature Subset Selection Using Cuckoo Search On IoT Network. International Journal of Advanced Networking and Applications, 11(6), 4475-4485.
- Khan, A., Khan, A., Bangash, J. I., Subhan, F., Khan, A., Khan, A., ... & Mahmoud, M. (2021). Cuckoo Search-based SVM (CS-SVM) Model for Real-Time Indoor Position Estimation in IoT Networks. Security and Communication Networks, 2021(1), 6654926.
- Kumar, M. S., & Karri, G. R. (2024). Scheduling Internet of Things tasks in cloud and fog computing environment using cuckoo search optimization. In Big Data and Blockchain Technology for Secure IoT Applications (pp. 1-21). CRC Press.
- Kurdi, H., Ezzat, F., Altoaimy, L., Ahmed, S. H., & Youcef-Toumi, K. (2018). Multicuckoo: Multi-cloud service composition using a cuckoo-inspired algorithm for the internet of things applications. IEEE Access, 6, 56737-56749.
- Liu, C., Wang, J., Zhou, L., & Rezaeipanah, A. (2022). Solving the multi-objective problem of IoT service placement in fog computing using cuckoo search algorithm. Neural Processing Letters, 54(3), 1823-1854.
- Nagavalli, S., & Ramachandran, G. (2019). An Efficient Routing Scheme Using Cuckoo Search Algorithm for Internet of Things. Journal of Computational and Theoretical Nanoscience, 16(5-6), 2045-2049.

- Sadeghi, F., & Avokh, A. (2020). Load-balanced data gathering in Internet of Things using an energy-aware cuckoo-search algorithm. International Journal of Communication Systems, 33(9), e4385.
- Sakamoto, S. (2024). Implementation of a cuckoo search intelligent simulation system for node placement problem in wireless mesh networks: Performance evaluation for tuning hyperparameters Pa and γ. Internet of Things, 27, 101288.
- Vakilian, S., Moravvej, S. V., & Fanian, A. (2021, May). Using the cuckoo algorithm to optimizing the response time and energy consumption cost of fog nodes by considering collaboration in the fog layer. In 2021 5th International Conference on Internet of Things and Applications (IoT) (pp. 1-5). IEEE.
- Yaseen, A., Nazir, M., Sabah, A., Tayyaba, S., Khan, Z. A., Ashraf, M. W., & Ahmad, M. O. (2020). Dimensionality reduction for internet of things using the cuckoo search algorithm: reduced implications of mesh sensor technologies. Wireless Communications and Mobile Computing, 2020(1), 8897026.
- Zhang, C., Zeng, G., Wang, H., & Tu, X. (2019). Hierarchical resource scheduling method using improved cuckoo search algorithm for internet of things. Peer-to-Peer Networking and Applications, 12(6), 1606-1614.