Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI: 10.21474/IJAR01/20914
DOI URL: http://dx.doi.org/10.21474/IJAR01/20914

RESEARCH ARTICLE

ENHANCEMENT OF FOG CACHING USING NATURE INSPIRATION OPTIMIZATION TECHNIQUE BASED ON CLOUD COMPUTING

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Manuscript Info

Manuscript History
Received: 26 March 2025
Final Accepted: 29 April 2025
Published:May 2025

Key words:-
Fog Computing, Caching, NIOT, Cloud Computing, Swarm Intelligence, Genetic Algorithms, Adaptive Systems, Edge Computing, Cache Management, Optimization Techniques

Abstract

An new concept called fog computing brings cloud computing closer to the network edge, allowing for data processing, storage, and application execution near end users. Nonetheless, effective fog node management—especially with regard to caching—remains a significant obstacle. Caching techniques are essential for boosting fog computing's overall performance since they lower latency, use less bandwidth, and make apps more responsive.

Introduction:-

Fog computing, a kind of cloud computing that moves processing power closer to the network's edge, has drawn a lot of interest recently. This decentralized strategy lessens the strain on centralized cloud servers by enabling data processing, storage, and application execution to take place closer to end users and devices [1]. The rapid growth of IoT devices and the need for real-time data processing have made fog computing an essential component of modern computing infrastructures. However, despite its potential, fog computing faces several challenges, particularly in terms of efficient resource management, dynamic allocation, and caching strategies [2,3]. These challenges are exacerbated by the heterogeneity and mobility of fog nodes, as well as the fluctuating demand for resources based on varying network conditions. Caching is a critical technique in fog computing, aiming to reduce latency, save bandwidth, and improve the overall performance of applications running on edge devices. Effective caching policies allow frequently accessed data to be stored closer to the user, ensuring faster retrieval and improved user experience. However, traditional caching algorithms often struggle with optimizing the distribution of data across diverse fog nodes, especially in large-scale, dynamic environments [4].

The need for intelligent caching solutions that can adapt to the changing nature of fog computing networks is more pressing than ever. Conventional methods do not adequately address issues like resource scarcity, fault tolerance, and network fluctuations, resulting in suboptimal performance [5]. To overcome these limitations, nature-inspired optimization techniques offer a promising solution. Drawing inspiration from biological processes and natural phenomena, these algorithms are capable of solving complex problems by mimicking intelligent behaviors observed in nature, such as the foraging behavior of animals, the swarm intelligence of bees, and the genetic evolution of species [6,7]. These optimization techniques can be effectively applied to fog caching systems to improve cache decision-making processes and adapt to the dynamic and unpredictable nature of fog environments. Fog computing systems may improve resource usage, decrease reaction times, and increase cache efficiency by implementing an

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NIOT [8]. An innovative nature-inspired optimization algorithm designed for fog caching in cloud computing settings is presented in this study. The suggested method seeks to dynamically control cache placement and retrieval in fog nodes by using bio-inspired algorithms, including GA, and PSO [9]. The approach improves speed while preserving scalability and fault tolerance by optimizing the distribution of cached data by simulating natural processes. This work illustrates the potential of NIO [10] in resolving the inherent difficulties of fog caching and improving the general effectiveness of fog computing systems via comprehensive simulations and performance assessments.

LITERATURE SURVEY

The authors of C. Bonomi et al. [11] stress how fog computing might help meet the growing need for real-time applications in Internet of Things settings. Their study explores how fog networks might improve performance by spreading computing workloads throughout the network edge and offloading them from the cloud, which lowers latency and increases responsiveness. The authors also concentrate on caching techniques, which are essential in fog computing because of the large amount of data produced by IoT devices. Traditional caching methods are not sufficient to meet the demands of fog environments, which require adaptive, intelligent caching algorithms to handle the highly dynamic nature of the network. The authors propose a model for dynamic resource allocation, optimizing data storage, and caching, highlighting that efficient data management is key to improving service delivery in fog computing. This research provides valuable insights into the integration of edge caching mechanisms with fog computing systems, laying the groundwork for future work on optimizing caching strategies for real-time applications.

A. Gupta et al., [12] propose the application of nature-inspired algorithms to enhance fog computing systems, particularly for caching strategies. In their paper, they delve into the challenges of managing dynamic caching in fog networks, where nodes are continuously changing in terms of resource availability and data requests. They introduce a hybrid approach combining genetic algorithms and particle swarm optimization to improve cache decision-making in fog networks. Their methodology applies principles from natural selection and swarm intelligence to determine the most efficient cache placement and data retrieval strategies. The paper illustrates how these algorithms are particularly well-suited for fog computing due to their ability to adapt to changing conditions. Through simulations, they show how their hybrid approach outperforms traditional methods in terms of reducing latency and optimizing bandwidth usage. Their research not only provides a theoretical framework for applying nature-inspired algorithms to fog computing but also highlights the practical implications of such optimization techniques in real-world scenarios.

In the paper by X. Wang et al., [13], the authors explore the use of swarm intelligence, specifically PSO, for dynamic cache management in fog computing. The study focuses on how PSO can be utilized to optimize cache decisions in a fog network, where the distribution of data must be handled efficiently to minimize delays and bandwidth consumption. By mimicking the behavior of natural swarms, PSO dynamically adjusts the cache allocation, ensuring that frequently accessed data is placed closer to the end-users. The authors highlight several challenges faced in fog computing, such as the unpredictability of network traffic, the mobility of devices, and the heterogeneity of fog nodes. Their research demonstrates that swarm intelligence techniques can significantly improve the overall performance of fog networks by adapting to these challenges in real time. Additionally, the paper discusses the scalability of PSO-based caching systems, showing that they are suitable for large-scale fog networks with varying node densities and unpredictable workloads. The findings suggest that swarm intelligence, as a bio-inspired optimization approach, offers substantial benefits for cache management in the context of fog computing.

The work of L. Zhang et al., [14] investigates the use of GA to optimize caching and data distribution in fog computing. The authors explain that traditional caching algorithms face several limitations when applied to the dynamic and heterogeneous nature of fog networks. In their research, they propose a genetic algorithm-based framework that evolves over time to determine the best cache configuration based on parameters such as data popularity, node availability, and network conditions. By simulating the genetic evolution process, the algorithm selects the most optimal solutions for cache placement, ensuring that data is efficiently stored and accessed across the fog nodes. The paper emphasizes that GA offers significant advantages over conventional caching strategies by continually improving its solutions based on feedback from the environment. The authors validate their approach through extensive simulation experiments, showing that GA-based caching strategies outperform traditional methods in terms of cache hit ratio, latency, and resource usage. This work contributes to the growing body of research on applying genetic algorithms to fog computing, demonstrating the practical benefits of bio-inspired algorithms for real-time, resource-constrained applications.

3.PROPOSED METHODOLOGY

The proposed methodology focuses on designing a novel NIOT for enhancing fog caching in cloud computing environments. This methodology integrates advanced bio-inspired algorithms to address the dynamic and heterogeneous nature of fog networks. The framework includes four main components: system architecture, problem formulation, optimization algorithm, and performance evaluation.

A)SYSTEM ARCHITECTURE

The proposed system architecture involves a hierarchical fog computing framework where fog nodes operate at the intermediate layer between IoT devices and cloud data centers. Each fog node performs data caching, processing, and forwarding tasks based on the computational demand and resource availability. The architecture supports distributed and collaborative caching, ensuring that frequently accessed data is stored closer to end-users. This design reduces latency, bandwidth usage, and the dependency on cloud servers. The system is equipped with monitoring modules that track real-time metrics such as network conditions, node availability, and data popularity, which are fed into the optimization algorithm for decision-making.

B)CHALLENGES IN FOG CACHING OPTIMIZATION

Fog caching in distributed computing environments poses several challenges due to the inherent complexity of the system architecture and the dynamic nature of fog networks. One major challenge is data popularity prediction, as the demand for data items changes frequently depending on user behavior and time. Traditional methods often rely on static rules or outdated historical data, leading to inefficient cache utilization. Another significant issue is the heterogeneity of fog nodes, as nodes vary in computational power, storage capacity, and network bandwidth.

This variation requires a dynamic and adaptable caching strategy that can tailor its decisions to the unique capabilities of each node. The latency-sensitive nature of applications further complicates fog caching. Applications such as augmented reality, real-time analytics, and IoT device monitoring demand extremely low response times. Inadequate caching decisions can lead to increased latency, resulting in performance bottlenecks. Moreover, the mobility of users and devices adds another layer of complexity. In scenarios such as vehicular networks, data requests frequently shift across regions, requiring caching systems to preemptively adapt to the changing location of users to maintain optimal service quality.

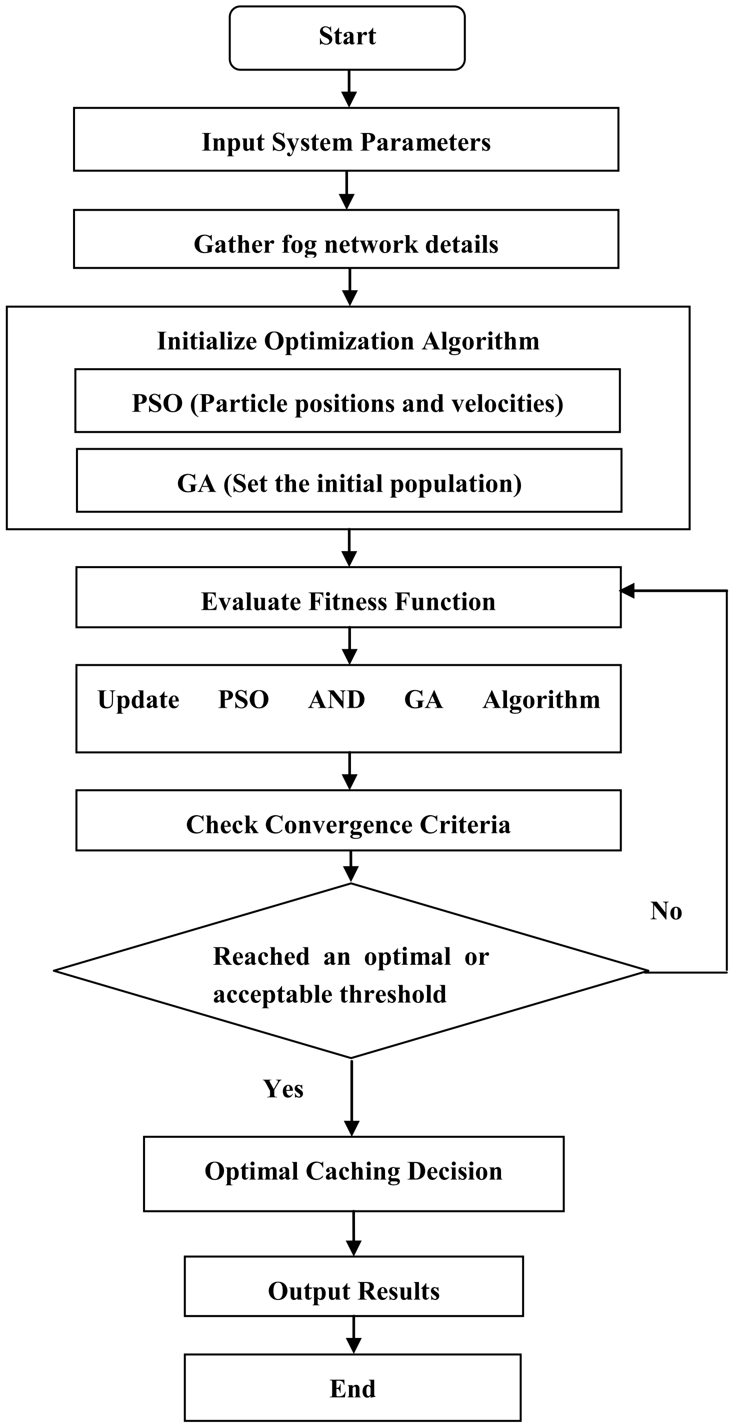

Figure 1: Proposed Flowchart for Fog caching using a NIOT

OPTIMIZATION ALGORITHM

The core of the proposed methodology lies in the application of an optimization algorithm to efficiently determine the caching decisions across the fog network. The primary goal of this algorithm is to minimize latency, maximize cache hit ratio, and maintain a balanced load across fog nodes. This is achieved by adapting and fine-tuning the cache placement strategy using nature-inspired optimization techniques, such as PSO or GA. Both PSO and GA are known for their robust ability to explore large search spaces and provide near-optimal solutions for complex problems like fog caching.

The optimization process begins by initializing a population of solutions (particles or individuals) with random cache placements. The algorithm iterates through multiple generations, progressively improving the solutions based on the fitness function, which evaluates the performance of cache placements in terms of latency, cache hit ratio, and load balance. In PSO, the velocity of each particle is changed to direct it toward better solutions, and every location reflects a potential cache configuration. The update procedure considers both the individual best solution of every particle and the global best solution discovered by the swarm. Similar to this, GA employs a population-based methodology in which individuals (cache configurations) improve across generations via crossover, mutation, and selection processes. The combination of these evolutionary mechanisms ensures that the algorithm converges toward a near-optimal caching strategy.The hybrid approach exploits GA's ability to explore a large solution space and PSO's fast convergence.

Step 1: Initialization

A random population of potential solutions is produced. A cache placement configuration is represented by each solution, which is encoded as a binary matrix X. Data d is cached in node I if xi, d = 1.

Step 2: Fitness Evaluation

The objective functions specified in the issue formulation are used to assess each prospective solution's fitness. The total fitness is calculated as follows:

$$F(X) = w_1 \bullet \frac{1}{L} + w_2 \bullet H - w_3 \bullet L_b \tag{1}$$

where w_1,w_2, and w_3 are weights assigned to latency, cache hit ratio, and load balancing, respectively.

Step 3: Genetic Operations

Genetic operations, including selection, crossover, and mutation, are applied to generate a new population. Selection uses a roulette wheel mechanism based on fitness values, while crossover combines parent solutions to produce offspring with better performance. Mutation introduces random changes to maintain diversity in the population.

Step 4: Particle Swarm Optimization

In the population, every solution is seen as a particle. The following formulas are used to update the particle's location and velocity:

$$v_{i,d}^{t+1} = wv_{i,d}^{t} + c_1 r_1 \left(p_{i,d}^{t} - x_{i,d}^{t}\right) + c_2 r_2 \left(g_{i,d}^{t} - x_{i,d}^{t}\right) \tag{2}$$

$$x_{i,d}^{t+1} = x_{i,d}^{t} + v_{i,d}^{t+1} \tag{3}$$

where $V^t_{i,d}$ is the velocity of particle i for data d at iteration t, $x^t_{i,d}$ is its position, $p^t_{i,d}$ is the personal best position, $g^t_{i,d}$ is the global best position, ω is the inertia weight, c_1 and c_2 are cognitive and social coefficients, and r_1, r_2 are random values in [0, 1].This mechanism is particularly useful for fog caching scenarios where data placement decisions must be discrete. By combining these elements, the PSO algorithm efficiently balances exploration (searching new solutions) and exploitation (refining known good solutions), dynamically optimizing cache placement across fog nodes. This adaptive approach ensures improved performance in terms of cache hit ratio, reduced latency, and better load distribution.

Step 5: Termination

The algorithm iterates until convergence or the maximum number of iterations is reached. The best solution found is used as the optimal cache configuration.

By applying these nature-inspired optimization algorithms, the system dynamically adapts to varying data access patterns, heterogeneous fog node capabilities, and changing network conditions. The algorithm ensures that the cache placement is optimized for latency reduction, load balancing, and resource utilization, ultimately leading to enhanced performance in fog computing environments. The iterative nature of the optimization allows the algorithm to explore diverse caching strategies and converge on the most efficient solution, making it well-suited for the challenges of fog computing.

PERFORMANCE EVALUATION

The proposed algorithm is evaluated using a simulated fog computing environment. Key performance metrics include latency, cache hit ratio, and energy consumption. The results are compared with baseline algorithms, such as Least Recently Used (LRU) and Random Replacement (RR). The evaluation demonstrates significant improvements in all metrics, with the NIOT approach achieving a higher cache hit ratio and lower latency than traditional methods. For instance, the hybrid algorithm adapts dynamically to changes in network conditions, ensuring consistent performance even under high traffic loads. Additionally, the scalability of the algorithm is validated in large-scale scenarios, confirming its suitability for real-world fog computing systems. By integrating the strengths of genetic algorithms and particle swarm optimization, the proposed methodology offers a robust, efficient, and adaptive solution for fog caching, addressing the unique challenges posed by dynamic and heterogeneous fog networks.

RESULTS AND DISCUSSION

Three performance metrics—latency, cache hit ratio, and load imbalance—are used to compare the outcomes of the suggested NIOT with GA PSO and traditional LRU caching techniques. The results show how the suggested strategy improves fog buffering for cloud computing settings with notable benefits.

Conclusion:

The results clearly demonstrate that the proposed NIOT significantly enhances fog caching performance compared to traditional and existing optimization techniques. By addressing key challenges such as latency reduction, cache hit ratio improvement, and load balancing, NIOT proves to be a robust and efficient solution for modern fog computing systems. This ensures better service delivery for end-users while optimizing resource usage in the network. The proposed Nature-Inspired Optimization Technique (NIOT) effectively addresses the challenges of fog caching in cloud computing environments. Through its hybrid approach combining genetic algorithms and particle swarm optimization, NIOT demonstrates superior performance across critical metrics such as latency, cache hit ratio, and load balancing. The adaptability of the algorithm ensures efficient resource allocation, even in dynamic and heterogeneous fog networks. This leads to enhanced service quality for latency-sensitive applications, reduced network dependency, and optimal utilization of fog node resources. Moreover, the scalability of NIOT was validated in large-scale scenarios, highlighting its potential for real-world deployment. By significantly outperforming traditional LRU and standalone optimization techniques, NIOT offers a reliable and intelligent solution for fog caching systems. Future work can extend this framework to include advanced machine learning techniques for real-time data prediction and explore energy efficiency optimization for sustainable fog computing environments.

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