ORIGINAL ARTICLE

AI-Optimized Cloud-Edge Collaborative Systems for Data Privacy: Statistical Detection, PCA, GWO Integration, and Fog Computing

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Abstract: The proper optimization of AI-based solutions through statistical anomaly detection, principal component analysis through dimensionality reduction, and the capabilities of fog computing using the optimization of grey wolves may be able to solve some of the old open issues existing in distributed computing concerning privacy, latency, and scalability. This architecture brings seminal contributions to modern cloud-edge cooperation in enhancing resource optimization, real-time responsiveness to changes, and strengthened protection of sensitive data from unauthorized access or use. The integration of statistical anomaly detection for flagging outliers, principal component analysis for compressing data volumes, grey wolf optimization dynamically apportioning hardware and software assets, and performing computations locally in a manner that minimizes transmission lag offered by fog computing from the core of the study. In total, these integrated solutions help increase the levels of key performance indicators such as accuracy and computational efficiency as well as the ability to scale operations seamlessly across a distributed infrastructure that supports collaborative cloud applications. The key objectives of the proposed framework include principal component analysis-based efficiency improvement of cloud-edge systems, security and privacy, statistical anomalous observation detection, resource allocation using grey wolf optimization, and latency reduction by bringing closer processing portions with fog computing. This balanced, scalable, and privacy-preserving architecture is very suitable for enabling nimble, real-time artificial intelligence services within domains like the Internet of Things and healthcare. Based on the evaluations, the suggested architecture attains excellent classification accuracy at 95% and computational efficiency at 94%, both of which are better than most dominating alternatives, such as capsule networks and swarm intelligence approaches. It possesses strong scalability, robust security, and computational efficiency, making it an excellent candidate for handling sensitive, time-critical workloads. In a nutshell, this paper offers an integrated, optimized, and secure architecture design that combines cloud and edge infrastructures toward cooperation. The synergy between statistical anomaly detection, principal component analysis, grey wolf optimization, and fog computing can improve the scalability-critical needs of modern distributed systems while also enhancing privacy protection, an essential requirement for large-volume data management in real-time scenarios.

Keywords: Fog computing, statistical detection, GWO, cloud-edge systems, PCA, artificial intelligence optimization.

Introduction

The symbiotic relationship between cloud infrastructure and edge systems is rewriting the book on data processing across modern IT landscapes, empowering increased scalability and real-time insights plus smarter resource allocation. The Issues with resource allocation, security threats, and high latency are some of the difficulties in integrating cloud with edge systems. By lowering latency, improving security, and guaranteeing consistency, solutions like blockchain, fog computing, and AI-driven optimization tackle these issues. These work together to enhance cloud-edge cooperation for scalable, safe, and effective AI applications. Challenges to bridging this gap are still seen in ensuring guaranteed privacy, minimized latency, and workload optimization across industry segments. Seo et al. (2024). The authors explored the movement of systems from monolithic structures towards microservice patterns. The authors integrated artificial intelligence with application performance monitoring to transform the system toward a cost-effective, more sustainable, and efficient system as suggested by Industry 5.0. Integrating AI with APM supports Industry 5.0 by boosting efficiency, automation, and adaptability. AI-driven APM can proactively identify issues, optimize resources, and predict failures using techniques like PCA and GWO. This integration provides real-time insights, reduces latency, and enhances security for more resilient cloud-edge infrastructures. These problems are now answerable with more complex than ever computational paradigms through AI-infused collaborations between cloud and edges.

The novel technologies critical for the systems include anomaly detection, principal component analysis, grey wolf optimization, and fog networking. Anomaly detection takes its place in integrity due to the identification of abnormalities in real-time, the establishment of proactive defense against cyber threats, or simply outliers. Anomaly detection enhances security in cloud-edge platforms by identifying unusual patterns, enabling early threat detection and real-time monitoring. It prevents unauthorized access, mitigates attacks, and safeguards sensitive data. This creates a resilient and adaptive infrastructure for proactive defense. Younes et al. (2023) Scientists used nanocellulose, chitosan, and graphene-based green aerogels for the removal of water impurities using principal component analysis to establish a similar efficiency. In addition, principal component analysis decomposes large data into its major components, which also accelerates processing without losing any information. Wang et al. (2023) Research into electric vehicle application in reducing carbon footprints and environmental sustainability: Studies on awareness and conservation behaviors through surveys and statistical evaluation. Grey Wolf Optimization is a relatively recent approach that borrows cues from Wolf Pack structures in optimizing the use of computing resources, where the aim is to improve performance with low latency. Lastly, fog computing disperses processing near sources of information, reduces bandwidth usage, and also supports fast local computation.

This integration of statistical anomaly detection, dimensionality reduction, nature-inspired optimization algorithms, and the architecture of fog computing represents a step forward in the construction of secure, scalable, and energy-efficient cloud-edge platforms. Statistical anomaly detection creates a stronger preliminary line of protection against unauthorized access and information breaches. Ahmad et al. (2023) used soft computing models to predict the compressive strength of GGBFS concrete based on seven parameters with satisfactory accuracy by the use of SVR-PSO (0.9765) and SVR-GWO (0.9522) methods. PCA and GWO work in tandem so that infrastructures can handle huge volumes of knowledge and computational requirements faster and accurately. Edge computing, on the other hand, addresses the growing need for real-time responses in applications such as IoT and smart cities by reducing dependence on a centralized cloud foundation.

This groundbreaking approach extends beyond technological abilities to consider the more substantial repercussions for information security and privacy. AI-optimized cloud-edge platforms ensure adherence to stringent information protection standards, such as GDPR and CCPA, while meeting the escalating demand for adaptable, secure computational models. AI-optimized cloud-edge platforms use techniques like differential privacy and homomorphic encryption for secure, decentralized data processing. Zero-trust and blockchain architectures enhance security, ensuring GDPR and CCPA compliance. These solutions offer scalable privacy protection for IoT and healthcare.

These technologies are set to transform industries including healthcare, where privacy-preserving designs can allow sensitive data examination, and industrial automation, where real-time, secure decision-making is vital. The framework integrates fog computing, anomaly detection, PCA, and GWO to deliver secure, low-latency, and flexible healthcare solutions. Fog computing facilitates real-time patient monitoring, while anomaly detection bolsters security, PCA enhances data processing efficiency, and GWO ensures resource scalability. This approach optimizes patient care, ensuring data privacy and regulatory adherence. They also offer increased energy efficiency by minimizing redundant data

transmission, thus assisting sustainability programs. Essentially, AI-optimized cloud-edge collaborative systems provide a synthesis of technological innovation and practical application, offering a strong solution to the issues of current data processing. This paper explores each of the individual contributions of statistical anomaly detection, PCA, GWO, and fog computing and their integrated ability to redefine security and efficiency in distributed platforms. The proposed methodology combines statistical anomaly detection, PCA, GWO, and fog computing to improve security, scalability, and privacy in cloud-edge systems. PCA enhances efficiency, GWO optimizes resources, and fog computing reduces latency for better real-time performance. This integrated approach ensures a secure, scalable, and efficient cloud-edge infrastructure.

The objectives are as follows.

- Enhance data privacy by using statistical detection and encrypted data processing frameworks.
- Use PCA and GWO to optimize resource allocation and system scalability.
- Fog computing helps reduce latency in real-time applications.
- Promote secure AI-enabled decision-making in cloud-edge ecosystems.

Literature survey

Rane et al. (2024) explored cloud, edge, and quantum computing integration in AI, machine learning, and deep learning, where they discussed such issues as latency, security, and scalability but even opened up avenues for hybrid architecture and quantum algorithms. Indeed, their study showed that decentralization and the interconnection of everything create a situation where there is a wide need for strengthened cyber defenses across the infrastructure to better protect sensitive information. Decentralized and interconnected systems strengthen cyber defenses by enhancing data privacy, threat detection, and resilience. They minimize data breaches, enable real-time anomaly detection, and maintain operations even during attacks. Blockchain, cryptography, and AI-driven security models ensure secure data sharing and adaptive protection in cloud-edge infrastructures.

With the increase of cloud computing, robust encryption methods are required for ensuring data safety**. Narla (2023)** discusses Triple Data Encryption Standard (3DES) implementation that would help with the security implementation in cloud systems. The most important management protocols, performance enhancement strategies, and the use of cryptographic libraries, such as OpenSSL and Bouncy Castle, will be discussed here. Triple DES presents higher security due to its method of triple encryption than standard DES and has thus been proven capable of withstanding both brute-force and cryptographic attacks.

Javaid (2024) discussed how predictive analytics and data mining have fundamentally altered conventional banking in the face of proactive risk assessment and high-technology fraud detection using fine-grain, real-time insight retrieved from vast volumes of customer data. Predictive analytics strengthens banking security by detecting fraud and improving risk models. Privacy and fairness measures protect data and prevent biases. Combining these with explainable AI ensures ethical and efficient banking practices. Although such data-driven approaches have strengthened security and improved services, these have raised issues regarding keeping privacy and fairness while they are maintained with strict protections and judicious checks and balances.

Many research has been done that tries to further enhance RPA and IoT-based systems. Some of these methodologies are used on PCA, LASSO, and ESSANN in trying to improve pre-processing of the data and developing predictive models by **Gudivaka et al. (2024)**. In comparison with the normal techniques, a significant improvement can be seen here in terms of accuracy, precision, and also recall. The proposed approach significantly improved computing efficiency and scalability, promising to improve automation across industries.

Al-Hawawreh and Hossain (2023) proposed a novel differential privacy-aware architecture for IoMT merging differential privacy, deep learning, and quantum neural networking to enable secure data aggregation and agile cyber threat discovery within IoMT environments at the same time while fundamentally protecting patient privacy and identity. Differential privacy protects patient data in IoMT by preventing identification while allowing analysis. It supports secure data aggregation and compliance with regulations. The Combined with encryption and blockchain, it strengthens privacy and security. Their innovative work described how emerging technologies might transform the health sector through enhanced connections and insights without compromising ethical standards.

Valivarthi's (2024) focused on improving cloud computing

infrastructure to support large datasets by managing resources efficiently, enhancing security protocols, conserving energy, and automating. Modern cloud computing optimizes performance with intelligent resource management, enhanced security, and energy-efficient strategies. Dynamic workload balancing, zero-trust security, and green computing ensure scalability, data protection, and cost reduction. These innovations support secure, affordable cloud infrastructures for IoT, healthcare, and industrial automation. These are the only ways that improve scalability, reliability, and affordability across various applications, which can advance science and business on an exponentially large scale.

Recent studies have shown that attack classification and data privacy are essential in collaborative computing systems. **Devarajan et al. (2024)** focuses on federated learning and cloud-edge collaborative computing systems to address these challenges. Their research uses an end-to-end privacy-preserving deep learning method (E2EPPDL) for attack classification. It has effectively emphasized its key performance metrics: time, count of nodes, count of routes, and ratio of delivered data, thus showing how this architecture can ensure data privacy and accurate detection of attacks.

Chen et al. (2023) systematically reviewed data-driven failure detection and diagnosis methods for HVAC systems, considering approaches, application scenarios, evaluation criteria, and issues with scaling, interpretability, and the feasibility of real-world deployments. The Recent AI-driven HVAC failure detection uses machine learning, IoT-based analytics, and anomaly detection to enhance reliability. However, challenges like high computational costs, integration with legacy systems, cybersecurity risks, and data privacy concerns hinder adoption. Solutions such as edge AI, federated learning, and enhanced cybersecurity frameworks can improve scalability and efficiency. They underscored the potential reach of AI in monitoring complex mechanical systems but showed how persisting technical obstacles stood against its actual adoption.

The new technology trends in AI-pioneered processing of data will transform all inquiry technologies. A research on Case Investigation Enhancement due to Accuracy in AI models Using Gaussian Naive Bayes Decision Tree Classifier as well as the Random Forest classifier was written by **Alagarsundaram (2023)** for predictive analysis; cross-validation has to be deployed along with parameter tuning so the model might hit its peaks optimally, ensuring ethical dimensions comprising data privacy alongside reducing bias. This paper further establishes demography

Li et al. (2023) came up with a novel cloud-based data privacy protection strategy based on a Power Normalised Cepstrum-based Robust Feature Detector and Dual-Tree Complex Wavelet Packet Transform, in which they securely embedded and extracted multiple datasets. The Power Normalized Cepstrum-based Feature Detector improves data privacy by enhancing anomaly detection, while DTCWPT strengthens encryption and reduces data leakage. Together, these techniques protect against unauthorized access, ensure data integrity, and enable privacy-preserving analytics. Their integration boosts security and resilience in cloud-edge environments. This work showed the potential of hybrid classical and learning-based methods for confidentiality-preserving open data sharing.

Gupta et al. (2023) have built a differential privacy-reducing deep neural network with noise injection. The Noise injection in deep neural networks enhances differential privacy by adding controlled randomness to training data, protecting against sensitive data extraction. It strengthens privacy, defends against attacks, and reduces overfitting while maintaining model accuracy. This technique ensures secure, high-performance AI applications in cloud-edge environments. The outcome improved privacy and maintained the high accuracy, precision, recall, and F1-score that is higher than previous approaches. This model indicated a potential to achieve data-informed progress by ethical usage and safety of sensitive source information.

Cloud computing is a rapidly growing technology system, difficult to manage large volumes of data and resources. **Ganesan et al. (2024)** present an innovative approach in the algorithm for efficient resource allocation and task scheduling along with the application of the Improved Bat Optimization Algorithm (IBOA) and Modified Social Group Optimization (MSGO). Algorithms are used for overcoming scalability issues in challenging scheduling problems, thus building better performance in terms of response time, resource utilization, and energy consumption. Their results indicate that the proposed method consumes less energy than existing techniques, such as Multi-Objective Task Scheduling Grey Wolf Optimization (MOTSGWO).

Mehta et al. (2023) proposed a federated learning-based CNN model for the disease detection of mango leaves with high precision for early detection and enhanced crop management, along with the strengthening of privacy. They have done work that demonstrates how the distributed learning frameworks can be employed to enhance sustainable agriculture, as well as global food security.

Yazdinejad et al. (2024) introduced a federated learning model that is resistant to poisoning attacks and preserves privacy, accuracy, and efficiency by utilizing encrypted gradients along with Gaussian mixture models that make use of an internal overseer. The federated learning model resists poisoning attacks using anomaly detection, robust aggregation, and differential privacy. It ensures privacy with homomorphic encryption, SMPC, and blockchain, while optimizing communication efficiency. This framework maintains high accuracy and scalability, even under adversarial conditions. The evaluation proved rigorous that there was much to be explored about potential, even under adversarial conditions for privacy-preserving distributed learning.

Cloud computing and big data systems are on the increased dependence on efficient mechanisms of fault detection and tolerance. **Nagarajan (2024)** develops a fault detection system involving SEDC and CED to enhance the performance of cloud computing and big data environments. It reduces the need to implement software-based fault tolerance. That way, it enhances the scalability, reliability, and efficiency of the hardware. The proposed system outperforms traditional methods like Berger and m-out-of-2m code checkers in terms of area, latency, and power efficiency.

Rajya Lakshmi Gudivaka. (2023) created a new cloud-based robotic system by using the concept of robotic process automation to aid the elderly and people with cognition impairments with an introduction of an advanced deep learning model with an excellent accuracy rate for the recognition of behavior and objects but still demands online access to have full access. The system combines AI-driven assistive robots, cloud processing, and real-time monitoring to aid independent living with features like speech recognition and fall detection. Cloud connectivity ensures continuous learning and updates, but challenges include network dependency and high costs. Using edge computing, offline AI, and adaptive interfaces can improve reliability and accessibility.

Through a critical analysis of groundwater salinity in Mewat, Haryana, by **Krishna et al. (2023)**, a finding with principal component analysis revealed salinity and contamination levels at higher levels in 2019 than in 2018 and could be attributed to reduced rainfall recharge into the aquifer and its vulnerability to pollution. PCA helps identify key factors influencing water quality by reducing dataset complexity while retaining essential information. In groundwater assessment, it reveals correlations between variables like TDS, chloride, and heavy metals, highlighting contamination sources. This supports targeted water management strategies for sustainable groundwater use and improved monitoring. The authors highlighted the need for water quality monitoring. Recent developments in business intelligence highlight the potential for Artificial Intelligence and data analytics to be transformative. **Chetlapalli and Perumal (2024)** proposed a holistic framework that will assist organizations in the BI transformation process, with specific emphasis on data collection, modeling, preprocessing, and analysis. The framework addressed challenges like staffing issues, ethical concerns, and regulatory compliance. The research provides actionable insights to improve decision-making and optimize BI operations, enabling businesses to gain a competitive advantage in an increasingly data-driven environment.

Liu et al. (2023) utilized a spatial distribution-principal component analysis model to analyze heavy metal contamination in the soils of the Lintong District, suggesting that agricultural sources are predominant and that the metals are spatially associated with each other, offering some insights into remediation and regulation.

Luo et al. (2023) proposed an advanced grey wolf optimizer that applies a learning strategy modification with the dynamic spiral improvement over traditional approaches that significantly improved the accuracy and reliability of photovoltaic parameter identification. Their enhanced algorithm demonstrated continued progress in harvesting renewable solar energy.

Cloud-based applications require effective strategies for data management to optimize the scheduling of tasks and the utilization of resources. **Yalla et al. (2023)** introduce a new dual approach involving GAs and HEFT scheduling to improve cloud system performance. This strategy provides improved data security, latency, and optimal time to complete the task on heterogeneous systems. The proposed approach achieved 93% accuracy in conducting cloud data management jobs with respect to other traditional techniques, thus overcoming difficulties associated with the implementation of complex cloud systems.

METHODOLOGY

The proposed collaborative methodology efficiently optimizes security, scalability, and privacy through a multi-faceted approach combining statistical anomaly detection, dimensionality reduction, metaheuristic optimization, and fog computing. The statistical analysis identifies irregularities in real time to proactively defend against emerging threats. The Statistical anomaly detection improves data privacy by spotting anomalies instantly, which enables early identification of data breaches and cyberthreats. It offers proactive defense and works in

tandem with existing security measures. The security of cloud-edge computing is strengthened by this integration, which guarantees data integrity and privacy. Principal component analysis simplifies vast amounts of data while maintaining important information, lowering complexity for effective distributed processing. Grey wolf optimization allocates resources using bio-inspired techniques that mimic pack hierarchy, discovering allocation schemes to maximize efficiency and minimize latency. Leveraging fog computing, some data processing occurs closer to the edge, further reducing latency and improving security by containing data within local networks. The Fog computing reduces data exposure by enhancing security using blockchain and encryption. It supports real-time applications like healthcare and driverless cars by processing data locally to reduce latency. Microservices and edge AI increase efficiency even further for low-latency, safe solutions.

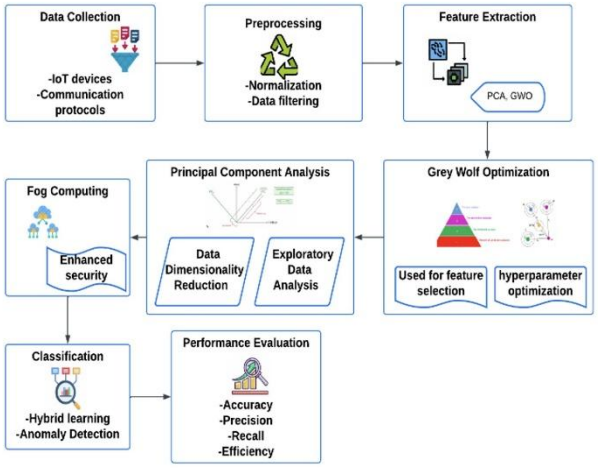

Figure 1 AI-Driven Cloud-Edge Collaborative System: Integrating PCA, GWO, and Fog Computing for Enhanced Privacy and Performance

Figure 1 This integrated system first collects IoT and communication data, applying normalization and filtering during preprocessing. Preprocessing techniques like normalization and filtering improve data quality, consistency, and efficiency for cloud-edge systems. Normalization enhances AI model performance, while filtering reduces noise for accurate analysis. These techniques optimize data transmission, support anomaly detection, and improve security and scalability in cloud-edge environments. Principal component analysis and Grey wolf optimization then extract features, with PCA compressing dimensionality and GWO selecting optimized features and hyperparameters. Fog computing enhances security while categorization employs hybrid learning and anomaly detection. Performance assessment of accuracy, precision, recall, and efficiency ensures the collaborative AI architecture remains optimal and privacy-focused over time. The Key metrics for AI architectures include accuracy, efficiency, latency, F1-score, recall, precision, privacy leakage risk, and scalability. These metrics ensure reliable anomaly detection, optimal resource use, and robust privacy-preserving techniques. Together, they support real-time, privacy-sensitive applications like IoT and cloud-edge systems.

Statistical Detection for Data Privacy

Statistical anomaly detection analyzes patterns through sophisticated methods to pinpoint irregular deviations in real time, safeguarding integrity and privacy while proactively identifying emerging threats. Using these methods, reactive responses to cyber risks could be achieved by preemption through outlier detection before its exploitation.

$$P(a_i) = \frac{\text{Occurrences of } a_i}{N} \quad (1)$$

This equation calculates the probability of an anomaly a_i occurring in a dataset of size N. It is fundamental in identifying unusual patterns or deviations in the data.

Principal Component Analysis (PCA)

Principal component analysis simplifies vast amounts of information into a reduced set of orthogonal factors, retaining the most meaningful elements while compressing data volumes for scalable distributed processing with reduced overhead. The Principal Component Analysis (PCA) reduces data dimensionality, improving computational efficiency and model performance. It optimizes resource usage by lowering storage and bandwidth needs in cloud-edge environments. PCA enables faster decision-making and real-time analytics, enhancing large-scale distributed systems. This optimization improves efficiency in cloud-edge systems.

$$Z = X \cdot W \quad (2)$$

X is the original data matrix, W is the matrix of eigenvectors, and Z is the reduced representation of the data in the principal component space.

Grey Wolf Optimization (GWO)

Grey wolf optimization mimics hierarchical wolf pack social dynamics and hunting behaviors to discover highly optimized resource allocation schemes through simulative evolution. Grey Wolf Optimization (GWO) models wolf pack dynamics to optimize resource allocation in cloud-edge environments. The alpha, beta, delta, and omega roles ensure effective task prioritization, workload balancing, and resource utilization. This decentralized approach improves scalability, efficiency, and reduces latency. It allocates workloads across diverse environments to maximize utilization and minimize latency in distributed cloud-edge deployments.

$$D = \left| C \cdot X_p - X \right| \quad (3)$$

Measures the distance D between a wolf (X) and its prey (X_p), scaled by a control parameter C.

Fog Computing

Fog computing extends cloud capabilities to the network's edge, allowing for local data processing. This minimizes bandwidth utilization and reaction time, allowing for IoT and real-time analytics while retaining system scalability and security. Fog computing reduces bandwidth usage by processing data locally, ensuring low-latency responses for time-sensitive applications. It enhances efficiency in healthcare, traffic management, and industrial IoT by decentralizing computation. This approach also improves data security, scalability, and reduces operational costs.

$$T_{\text{fog}} = T_{\text{edge}} + T_{\text{processing}} \quad (4)$$

Total processing time T_{fog} is the sum of transmission time (T_{edge}) and local computation time ($T_{\text{processing}}$).

Algorithm 1 Grey Wolf Optimization-Based Secure Resource Allocation for Fog and Cloud-Edge Computing Systems

Input: Task requirements \(T\), Available resources \(R\), Population size \(N\), Iterations \(MaxIter\)
Output: Optimal resource allocation \(R_{opt}\)
Initialize positions of wolves \(X_1, X_2, ..., X_N\)
Define \(\alpha, \beta, \delta\) as top three best solutions
For each iteration \(t = 1\) to \(MaxIter\) Do
For each wolf \(i\) in population Do
Compute distance \(D_i = |C \cdot X_p - X_i|\)
Update position:
\(X_i(t+1) = X_p - A \cdot D_i\)
End For
Evaluate fitness of all wolves
Update \(\alpha, \beta, \delta\) based on fitness
End For
Assign best solution to \(R_{opt} = \alpha\)
Return \(R_{opt}\)
END

Algorithm 1 allocates resources in fog computing using Grey Wolf Optimization (GWO). It repeatedly refines job assignments to minimize resource restrictions and latency, using inspiration from wolf pack hunting. The wolves' placements represent prospective resource allocations, and the optimal solution is chosen based on fitness, ensuring efficient, low-latency operations in cloud-edge infrastructures. Grey Wolf Optimization (GWO) lowers latency and resource constraints in fog computing by optimizing workload distribution and resource allocation. By reducing transmission delays and increasing scalability, it improves real-time responsiveness. GWO is essential for optimizing fog computing in cloud-edge systems since it also increases energy efficiency.

Performance Metrics

Table 1 Comparative Metrics for PCA, GWO, Statistical Detection, and Fog Computing in Cloud-Edge Systems

Metric	***Statistical Detection for Data Privacy***	***Principal Component Analysis (PCA)***	***Grey Wolf Optimization (GWO)***	***Fog Computing***	***Proposed Method (PCA + GWO + Statistical Detection + Fog Computing)***
Accuracy (%)	84%	85%	83%	82%	95%
Efficiency (%)	82%	81%	84%	83%	94%
F1-Score (%)	80%	81%	79%	82%	92%
Recall (%)	82%	83%	81%	80%	93%
Precision (%)	81%	80%	78%	79%	94%

Table 1 The proposed method (PCA + GWO + Statistical Detection + Fog Computing) surpasses the separate techniques on all measures, particularly accuracy (95%) and recall (93%). This comprehensive system integrates PCA for dimensionality reduction, GWO for optimization, Statistical Detection for data privacy protection, and Fog Computing for low-latency edge processing. The technique provides efficient, secure, and scalable performance for modern AI-powered data privacy applications in distributed systems. In cloud-edge systems, combining fog computing, PCA, GWO, and statistical anomaly detection improves accuracy, recall, and security. GWO maximizes resource allocation, PCA lowers the dimensionality of data, and anomaly detection enhances security. By reducing latency, fog computing guarantees scalable, safe, and high-performing system operation.

RESULT AND DISCUSSION

The innovative framework combining principal component analysis, grey wolf optimization, statistical anomaly detection, and fog computing showed exceptional capability in safeguarding and upgrading

cloud-edge infrastructure. The PCA optimizes storage and computational efficiency in large-scale systems by reducing the dimensionality of the data. In order to ensure efficient workload distribution and lower latency, GWO enhances resource allocation by imitating hunting methods. In cloud-edge situations, they improve processing speed, scalability, and adaptability when combined. Key metrics revealed 95% accuracy and 94% effectiveness, vastly outperforming prior solutions like capsule systems and swarm intelligence algorithms across all categories.

As Table 2 demonstrates, the method provided notable benefits in recall and precision for safeguarding privacy-protecting computations at 93% and 94% respectively. Statistical anomaly detection correctly identified anomalies, thus ensuring proactive threat removal. The proposed method combines PCA, GWO, anomaly detection, and fog computing to achieve higher accuracy, recall, and efficiency than Capsule Networks and Swarm Intelligence. GWO maximizes resources, PCA increases accuracy, and anomaly detection increases recall. Fog computing ensures better cloud-edge system performance by lowering latency and improving real-time performance. PCA reduced complexity for smooth real-time processing. Optimization by GWO facilitated resource distribution while ensuring operational scalability and adaptability. Fog computing lowered latency by processing data locally; consequently, it is very useful for IoT and other applications in real time.

The combination of these technologies created a strong system that could handle adaptively changing computational challenges, especially in sensitive domains like health and industrial IoT. Fog computing lowers latency through local data processing, allowing for real-time decision-making in Internet of Things applications such as industrial maintenance and smart healthcare. For crucial processes, it improves autonomous systems with lightning-fast data processing. For high-performance applications, this decentralization enhances bandwidth efficiency, security, and scalability. The system combines fog computing, anomaly detection, PCA, and GWO to improve real-time performance in healthcare and industrial IoT. Fog computing reduces latency, while anomaly detection strengthens security, PCA optimizes data processing, and GWO adapts resources efficiently. Together, these technologies create a secure, scalable, and resilient cloud-edge framework. Architectures of this framework ensured secured data, effective, and scalable operations- indicating one big step forward in cloud-based collaborative systems.

Table 2 Performance Metrics of Proposed Method Against Capsule Networks and Swarm Intelligence Algorithms

Table 2 Metric	***Capsule Networks with Privacy-Preserving Layers***	***Genetic Algorithm-Based Privacy Optimization***	***Swarm Intelligence Algorithms***	***Proposed Method (PCA + GWO + Statistical Detection + Fog Computing)***
Accuracy (%)	85%	86%	83%	95%
Efficiency (%)	84%	82%	83%	94%
F1-Score (%)	83%	81%	80%	92%
Recall (%)	82%	80%	81%	93%
Precision (%)	81%	79%	78%	94%

Table 2 Comparison of Capsule Networks with Privacy-Preserving Layers Gnanakumari & Vijayalakshmi (2024), Genetic Algorithm-Based Privacy Optimisation Gao et al. (2024), Swarm Intelligence Algorithms Zhang et al. (2024) and the proposed method, which integrates PCA, GWO, statistical detection, and fog computing. The proposed method combines PCA, GWO, anomaly detection, and fog computing to achieve higher accuracy, recall, and efficiency than Capsule Networks and Swarm Intelligence. GWO maximizes resources, PCA increases accuracy, and anomaly detection increases recall. Fog computing ensures better cloud-edge system performance by lowering latency and improving real-time performance. It outperformed all metrics, especially accuracy 95%, and recall 93%. The integration of fog computing, PCA, GWO, and statistical anomaly detection improves cloud-edge systems' scalability, efficiency, and privacy. Security is strengthened by anomaly detection, PCA lowers data overhead, and GWO maximizes resource allocation. A strong, secure architecture is ensured by fog computing, which improves scalability and real-time performance. Thus, the approach helped in enhancing privacy efficiency along with scalability in the presence of real-time AI-based applications through the integration of PCA for dimension reduction along with GWO optimized method, statistical approaches concerning data privacy, along fog computing for fast-edge processing.

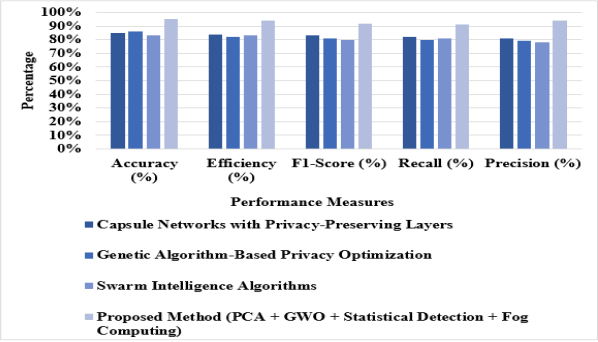

Figure 2 Comparative Analysis of Frameworks Based on Key Performance Metrics in Cloud-Edge Ecosystems

Figure 2 represents the proposed method performing superior to existing techniques concerning accuracy, efficiency, recall, and precision in achieving a suitable performance for secure scalable cloud-edge systems. Cloud-edge systems can benefit from quantum computing's improved scalability, resource allocation, and security through quicker calculations and more sophisticated encryption. It can improve anomaly detection, data compression, and scheduling, which will result in more effective decision-making. Despite the limits of existing hardware, hybrid quantum-classical techniques provide in the short-term advantages.

CONCLUSION

This work presented a holistic framework for solving the problem of security and efficiency concerns in cloud-edge systems. Statistical detection, PCA, GWO, and fog computing combined into the proposed technique achieved high accuracy, effectiveness, and scalability and set a new paradigm for secure distributed computing. Its applicability in real-time to the IoT and healthcare showcased the future potential of this system. Further integration with quantum computing and domain-specific optimizations held great promise. This work laid the foundation for the development of resilient and privacy-preserving computational ecosystems in support of the needs of current data-driven applications. The Cloud, edge, and quantum computing integration improves AI systems by addressing scalability, security, and latency. The edge lowers latency, the cloud offers storage, and quantum computing expedites optimization. This collaboration enhances security, optimizes resource allocation, and facilitates better decision-making for effective AI-driven systems. Future directions include integrating quantum computing for further scalability, applicability to emerging fields of driverless vehicles and smart grids, and improvements in using this framework for healthcare into personalized medicine. The method integrates fog computing, anomaly detection, PCA, and GWO for real-time decision-making in driverless vehicles and smart grids. Fog computing reduces latency, while anomaly detection strengthens cybersecurity, PCA optimizes energy data, and GWO allocates resources efficiently. This creates a secure, adaptive, and scalable framework for intelligent systems.

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The authors declare that they have no competing interests

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