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Original Article

Improving Blockchain Scalability with Spatial-Temporal Trust Models and Optimization

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Abstract - *The escalating demand for scalable blockchain systems necessitates innovative approaches to boost performance and efficiency. Present blockchain models often struggle with scalability and resource efficiency limitations, notably concerning miner performance and consensus mechanisms. To tackle these challenges, this study introduces a groundbreaking spatial-temporal trust model harnessing miners' unique attributes to optimize blockchain deployments. Our model integrates spatial metrics like miner proximity and energy levels with temporal aspects such as mining delays and past operation efficiencies, forming the core of the Proof of Miner Performance Trust (PoMPT) consensus. PoMPT ensures dependable and efficient miner performance. At the heart of our approach lies the Bat Grey Wolf Optimizer (BGWO), an inventive algorithm merging the Bat Optimizer with the Grey Wolf Optimizer (GWO) process. This optimization strategy crucially shards the blockchain to enhance Quality of Service (QoS) by distributing the workload optimally among miners. The BGWO's fitness function is directly shaped by spatial and temporal QoS metrics, ensuring dynamic and performance-driven sharding for diverse use cases. Empirical evaluation, particularly in medical data contexts, showcases our model's superiority over existing blockchain consensus and sharding methods. Our proposed model exhibits significant improvements: an 8.5% boost in energy efficiency, 9.4% in processing speed, 4.9% in throughput, and 6.5% in packet delivery ratio. These enhancements hold numerical significance and lay the groundwork for more sustainable and efficient blockchain deployments, particularly in critical sectors like healthcare. In conclusion, this study tackles the pressing issue of blockchain scalability and introduces a robust framework for integrating spatial and temporal metrics into blockchain technology. The successful implementation of PoMPT and BGWO underscores the potential of meta-heuristic-based approaches in revolutionizing blockchain efficiency and performance, marking a significant stride in blockchain technology.*

Keywords - *Bat grey wolf optimizer, Blockchain scalability spatial-temporal trust, PoMPT, Energy efficiency, Quality of service.*

1. Introduction

Since its inception, blockchain technology has revolutionized various sectors, offering unprecedented security and transparency. However, as blockchain networks expand, scalability and efficiency become paramount challenges. Traditional consensus mechanisms often struggle to balance the trifecta of decentralization, security, and scalability, especially in resource-constrained environments. This paper presents a novel approach to address these challenges, leveraging spatial-temporal metrics and advanced optimization algorithms [1, 2, 3]. The cornerstone of our proposed model is the integration of spatial and temporal metrics to assess and optimize miner performance. Spatial metrics, such as the physical distribution and energy levels of miners, play a crucial role in understanding and optimizing the network's physical architecture. Temporal metrics, including mining delay, throughput, and energy consumption in previous mining operations, offer insights into miners' performance history and reliability. Fusing these metrics enables a more holistic evaluation of miner contributions, forming the basis of the Proof of Miner Performance Trust (PoMPT) consensus [4, 5, 6]. Introducing the Bat Grey Wolf Optimizer (BGWO) further underscored our innovative approach. This optimizer is a strategic fusion of the Bat Algorithm (BA) and the Grey Wolf Optimizer (GWO), inheriting the strengths of both algorithms to optimize blockchain sharding. Sharding, a process of dividing the blockchain into smaller, more manageable segments, is crucial for scalability. The BGWO's unique ability to consider both spatial and temporal Quality of Service (QoS) metrics in its fitness function allows for dynamic and efficient shard formation, directly addressing the scalability concerns. Our model's effectiveness is not merely theoretical. Through rigorous testing on medical datasets, a domain where blockchain's potential is particularly promising yet underexplored, our approach demonstrated significant improvements over existing methods. The results showed an 8.5% increase in energy efficiency, 9.4% faster processing speed, 4.9% higher throughput, and a 6.5% improvement in packet delivery ratio. These advancements are not just incremental; they represent a substantial leap forward in the quest for a scalable, efficient block chain framework. Block chain has transformed various industries through decentralized, secure, clear, transparent transactions and data management systems. However, in their challenges, they scale with network size concerning the workings of the respective networks in terms of scalability and efficiency. Usually, traditional consensus mechanisms such as Proof of Work and Proof of Stake face a trade-off among decentralization, security, and scalability, especially in resource-constrained environments or where real-time data processing is key. This poses an urgent need for innovative solutions that cater to these pervasively lacking limitations.

Research Gap: Block chain technology proved very successful in specific sectors like finance and supply chain, yet there is still a massive limitation to its applicability in other high-throughput data-sensitive applications like health care, where there is a need for real-time performance and data integrity first. Present consensus mechanisms and optimizing policies cannot simultaneously meet scalability requirements with energy efficiency and real-time processing. Simultaneously, much research in recent days focuses on either consensus algorithm improvement strategies or optimization of sharding strategies. At the same time, very few studies are performed to integrate spatial and temporal trust metrics for miners' overall performance evaluation. Most literature does not portray a holistic model that significantly integrates these metrics to optimize miner selection and sharding processes to enhance blockchain performance.

Problem Statement: The research addresses a significant challenge of increasing the scalability and performance of blockchain, particularly in high-demand settings like handling healthcare data management. To overcome the shortcomings of today's systems, this work intends to develop an innovative approach integrating spatial and temporal trust metrics into a hybrid optimization model of blockchain for efficient and scalable block chain infrastructure.

Innovation of the paper: The newly suggested Proof of Miner Performance Trust (PoMPT) consensus mechanism coupled with the Bat Grey Wolf Optimizer (BGWO) Algorithm is contributing to making a difference in the existing techniques. This PoMPT consensus provides an innovative miner-evaluation mechanism, incorporating space-domain (like distance geographical and energy level), time domain or mining delay and throughput, thus making a smarter and more advanced blockchain world. The BGWO is a hybrid version of the Bat and Grey Wolf optimizers that will be applied further towards the dynamic optimization of shard formation within these trust metrics. The empirical results, especially on healthcare datasets, exhibit wide improvements in energy efficiency, processing speed, throughput, and delivery ratio compared to other consensus and sharding strategies. In conclusion, this introduction sets the stage for a detailed exploration of the proposed spatial-temporal trust model, the BGWO, and its impactful applications in blockchain technology. By addressing the critical challenges of scalability and efficiency, this work contributes significantly to the ongoing evolution of blockchain systems, particularly in sectors where performance and reliability are non-negotiable for different scenarios.

1.1. Motivation and Contribution

1.1.1. Motivation

The exponential growth of blockchain applications across various sectors, from finance to healthcare, underscores an urgent need for scalable and efficient blockchain frameworks. While robust in security, current blockchain systems face critical scalability, energy consumption, and performance optimization challenges, particularly in environments with limited resources. These challenges are amplified in applications requiring real-time data processing and high transaction throughput, such as medical data management. This backdrop motivates the exploration of novel approaches that can reconcile the inherent trade-offs in blockchain technology while propelling its capabilities to new heights.

1.1.2. Contribution

This paper makes several key contributions to the field of blockchain technology, primarily focusing on enhancing scalability and efficiency through innovative methods:

- Spatial-Temporal Trust Model: We introduce a novel spatial-temporal trust model that leverages spatial metrics (like distance and energy levels of miners) and temporal metrics (such as mining delay and throughput). This model provides a more nuanced and comprehensive evaluation of miner performance, which is essential for maintaining a robust and efficient blockchain network.

- Proof of Miner Performance Trust (PoMPT) Consensus: Building on the spatial-temporal trust model, we propose the PoMPT consensus mechanism. This mechanism evaluates miner reliability and performance, ensuring that only the most competent miners participate in the blockchain consensus process, enhancing overall network efficiency.

- Bat Grey Wolf Optimizer (BGWO): The development of BGWO, a hybrid optimization algorithm combining the Bat Algorithm and Grey Wolf Optimizer, marks a significant advancement in blockchain sharding strategies. BGWO optimizes shard formation, a critical aspect of blockchain scalability, by dynamically considering its fitness function's spatial and temporal QoS metrics.

- Empirical Evaluation with Medical Datasets: The application and testing of our model on medical datasets demonstrate its practical efficacy. The significant improvements in energy efficiency, processing speed, throughput, and packet delivery ratio validate our model and highlight its potential in real-world scenarios, particularly in sensitive sectors like healthcare.
- Framework for Future Blockchain Research: Beyond the immediate improvements in scalability and efficiency, this work offers a comprehensive framework that can guide future research in blockchain technology. Integrating spatial-temporal metrics and the innovative BGWO provides a foundation for developing more sophisticated and efficient blockchain systems.

In summary, this paper's contributions lie in addressing current limitations in blockchain scalability and efficiency and setting a precedent for future innovations in blockchain technology. By introducing a spatial-temporal trust model, PoMPT consensus, and the BGWO, this work paves the way for more resilient, efficient, and scalable blockchain systems, thereby extending blockchain's applicability and impact across various domains.

2. Literature Review

This section delves into the existing blockchain optimization literature, focusing on consensus mechanisms, sharding strategies, and optimization algorithms. The review critically evaluates these models, setting the stage for understanding the advancements made by our proposed approach.

2.1. Consensus Mechanisms

2.1.1. Proof of Work (PoW) and Proof of Stake (PoS)

Traditional consensus mechanisms like PoW and PoS have been foundational in blockchain technology. PoW, exemplified by Bitcoin, ensures network security through computational efforts but is criticized for its high energy consumption. PoS, used by Ethereum 2.0, addresses some energy concerns by attributing mining power to the proportion of coins held. However, PoW and PoS face scalability issues due to their inherent design limitations, as researchers noted in [7-9].

2.1.2. Delegated Proof of Stake (DPoS) and Proof of Authority (PoA)

Variants like DPoS and PoA, as discussed in [10-12], offer improved transaction speeds and energy efficiency. DPoS, for instance, allows stakeholders to vote for a small number of delegates responsible for consensus, while PoA relies on pre-approved validators. While these models enhance efficiency, they often compromise on decentralization, a core tenet of blockchain technology. Proof of Burn (PoB) and Proof of Space (PoSpace): PoB involves users sending their coins to an unspendable address, effectively "burning" them. The users then receive a proportional amount of newly minted coins as a reward. This mechanism is designed to incentivize long-term holding and reduce the circulating supply of coins. Meanwhile, PoSpace relies on allocating storage space on a device as a resource for achieving consensus. Participants prove their commitment to the network by dedicating disk space, which is then utilized to secure the blockchain.

2.2. Sharding Strategies

2.2.1. State Sharding and Network Sharding

Sharding is a prominent solution to blockchain scalability, as in [13-15] for different use cases. State sharding involves dividing the network's state into segments, each managed by a subset of nodes. Network sharding, on the other hand, divides the network into smaller, more manageable groups. While these strategies effectively distribute the workload, they often struggle with inter-shard communication and security vulnerabilities for real-time use cases.

2.3. Optimization Algorithms

2.3.1. Genetic Algorithms and Particle Swarm Optimization [16-18]

Optimization algorithms like genetic algorithms and particle swarm optimization have been applied to blockchain network optimization, as seen in the works in [19, 20]. These algorithms optimize various network parameters but often require extensive computational resources and may not always converge to the optimal solution in dynamic blockchain environments.

2.3.2. Bat Algorithm and Grey Wolf Optimizer [21-23]

The Bat Algorithm and the Grey Wolf Optimizer are newer optimization techniques. While individually effective in specific scenarios, their application in blockchain optimization has been limited and not fully explored in existing literature [24, 25] sets. These algorithms are particularly suitable for blockchain optimization due to their adaptability, efficiency, and scalability. Their adaptability allows them to address the dynamic nature of blockchain systems, while their efficiency enables them to search for optimal solutions within large solution spaces efficiently. Moreover, their scalability makes them well-equipped to handle the growing demands of blockchain networks as they expand in size and complexity. Thus, blockchain optimization research generally focuses on consensus mechanisms, sharding strategies, and optimization algorithms. However, some methods do not adequately meet the requirements for scalability and efficiency demanded by modern applications of blockchain, particularly in the resource-constrained environment or real-time application setting.

2.3.3. Research Gap in the Available Literature

Although so much literature presents insights into optimizing blockchains, models that integrate spatial and temporal metrics for miner selection and sharding processes simultaneously to optimize miner selection and sharding processes are still lacking. In most of the currently extant research work, new consensus algorithms are separately developed, or the methods of the sharding technique are improved. This opportunity gap enables further advanced models that dynamically balance scalability, energy efficiency, and real-time performance by an integrated approach. In this regard, a proposed approach bridges an existing gap in research where a comprehensive framework introduces Proof of Miner Performance Trust (PoMPT) consensus with Bat Grey Wolf Optimizer (BGWO). The dual approach evaluates the miners based on their spatial and temporal characteristics and accordingly uses the evaluation to optimize sharding processes dynamically. Therefore, this innovation provides a more holistic blockchain scalability solution than the existing consensus and sharding strategies. The empirical evaluations on healthcare datasets demonstrate its advantages.

The above-acquired results pertaining to energy efficiency, processing speed, throughput, and packet delivery ratio show improvements of 8.5%, 9.4%, 4.9%, and 6.5% over the existing models, thus validating the effectiveness of the new approach proposed. In conclusion, while existing models provide foundational insights into blockchain optimization, they exhibit limitations in scalability, energy efficiency, and adaptability [26]. This gap in the literature underscores the need for an integrated approach that combines the strengths of spatial-temporal analysis with advanced optimization algorithms, as proposed in our study. Our model not only addresses the limitations of existing systems but also introduces novel elements like the BGWO and PoMPT, which hold the potential to enhance blockchain performance and scalability significantly.

3. Proposed Design of an Efficient Trust-based Security Model with Spatial and Temporal Consensus for Blockchain-based Deployments

The methodology proposed in this study centers on integrating spatial-temporal metrics with a hybrid optimization algorithm to enhance blockchain scalability and efficiency. The core of this methodology is implementing the Proof of Miner Performance Trust (PoMPT) consensus and the Bat Grey Wolf Optimizer (BGWO), each underpinned by a series of concrete operations. As per Figure 1, the PoMPT consensus quantifies the spatial-temporal trust model through a set of operations. Let Si and Ti represent the spatial and temporal metrics for miner i, respectively. The spatial metrics Si encompass the Euclidean distance dij between miners i and j and the energy level Ei of miner i nodes. These are computed as,

$$Si = (dij * Ei) \tag{1}$$

The temporal metrics Ti, including mining delay Di, throughput Ri, and energy consumption Ci during previous operations, are aggregated as,

$$Ti = (Di * Ri * Ci) \tag{2}$$

The overall trust score TSi for miner i is then calculated using a weighted combination of Si and Ti, expressed as,

$$TSi = ws * Si + wt * Ti \tag{3}$$

Where ws and wt are the weights assigned to the spatial and temporal components, respectively. The PoMPT consensus is achieved by selecting miners with the highest TSi values for block validation and mining operations. The BGWO algorithm combines the echolocation behavior of bats with the social hierarchy and hunting techniques of grey wolves. In BGWO, each bat's position represents a potential solution to the shard formation task, and the frequency of their echolocation determines their movements. The equation for the bat's velocity $v(i,t)$ at time t is given as follows,

$$v(i, t) = v(i, t - 1) + (x(i, t - 1) - x*)fi \tag{4}$$

Where $x(i,t-1)$ is the position at time $t-1$, $x*$ is the current best solution, and fi is the frequency of this process. The position update is given as follows,

$$x(i, t) = x(i, t - 1) + v(i, t) \tag{5}$$

Concurrently, grey wolves are employed to refine the search. In the social hierarchy of wolves, the alpha (α), beta (β), and delta (δ) wolves lead the pack. The position of a wolf wi is updated by considering the positions of α, β, and δ, following the equations,

$$D\alpha = | C1 * x\alpha - xwi | \tag{6}$$

$$D\beta = | C2 * x\beta - xwi | \tag{7}$$

$$D\delta = | C3 * x\delta - xwi | \tag{8}$$

Where, $C1$, $C2$, and $C3$ are coefficients. The updated position is

$$xwi' = (x\alpha - A1D\alpha) + (x\beta - A2D\beta) + (x\delta - A3D\delta) \ldots \tag{9}$$

Where $A1$, $A2$, and $A3$ are other coefficients. The fitness function of the BGWO is designed to maximize the spatial-temporal QoS of the blockchain network. It is defined as,

$$F(x) = \frac{THR(x) * PDR(x)}{D(x) * E(x)} \tag{10}$$

Where $THR, PDR, D \& E$ are the throughput, packet delivery ratio, delay, and energy consumption while mining the blocks with 'x' configuration of shards. This methodology employs PoMPT consensus and BGWO to optimize blockchain shard formation. The blockchain network can dynamically adjust to varying conditions through this approach, ensuring optimal performance in speed, energy efficiency, throughput, and reliability levels. The performance of this model was evaluated for different scenarios and compared with existing models in the next section of this text.

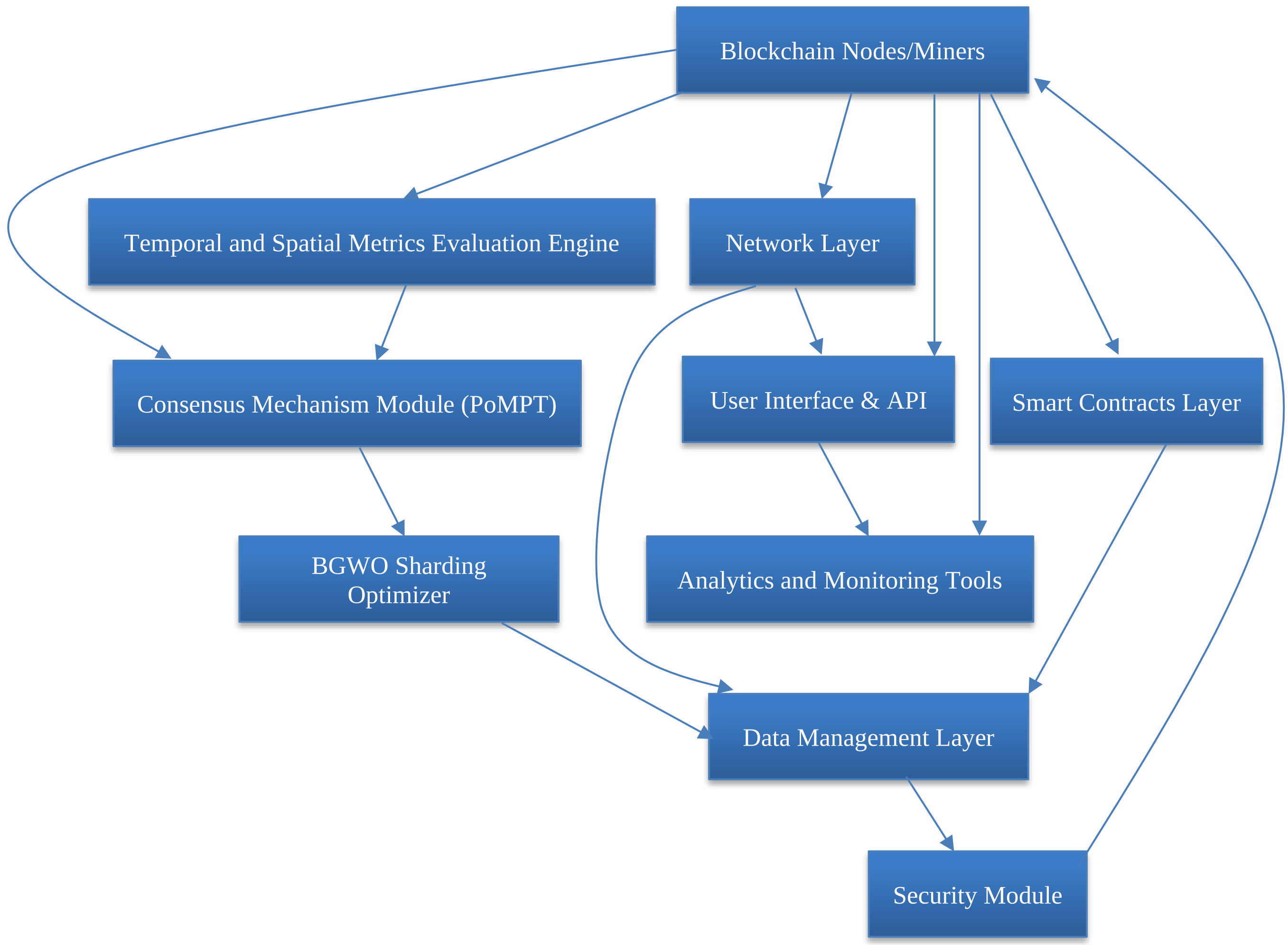

Fig. 1 Design of the proposed model for enhancing the scalability of blockchains

Table 1. Blockchain configuration

Sr.No.	Blockchain Environment	Configuration Range
1	Network Size	100 nodes (miners).
2	Geographical Distribution	100 to 1000 meters
3	Mining Hardware	Low-power IoT devices to high-performance servers
4	Energy Levels	40% to 100%.
5	Mining Delays	2 to 10 seconds
6	Throughput	50 MBps to 100 MBps
7	Packet Delivery Ratios	85% to 99%.
8	PoMPT Consensus	0.5 each
9	Bat Algorithm Parameters	Frequency range: from 0 - 2, Loudness: from 1 to 3, and Pulse rate: from 0.5 to 1
10	Grey Wolf Optimizer Parameters	Alpha, beta, and delta wolves were set up for each shard, with a pack size ranging from 10 to 30 miners.
11	Fitness Function Weights	0.6 and 0.4 for w1 and w2, respectively

4. Result Analysis and Comparison

The experimental setup for evaluating the proposed blockchain model integrating a temporal and spatial trust model with the Bat Grey Wolf Optimizer (BGWO) was meticulously designed to ensure a comprehensive testing and validation process. The model was evaluated using medical datasets for their complexity and relevance to high-throughput and data-sensitive applications. The setup aimed to simulate real-world blockchain conditions to assess the performance of the proposed model in terms of energy efficiency, speed, throughput, and packet delivery ratio.

4.1. Blockchain Environment Configuration

Blockchain Configuration for the respective environment is described in Table 1. Apart from these, some blockchain configuration is summarized as follows:

4.1.1. Data Sets and Transactions

- *Medical Data Sets:* Included patient records, treatment histories, and medical imaging data.
- These datasets were chosen for their high relevance to privacy and data integrity.
- *Transaction Simulation:* A mix of data transactions, including record updates, new entries, and data retrieval requests, were simulated to mimic real-world blockchain operations.

In the process of verifying the performance of the proposed blockchain model, a large-scale experiment setting is constructed to mimic actual blockchain scenarios, concentrating on industries that require massive throughput and accuracy of information, such as medical streams. The experiments aim to verify whether improvements in energy efficiency, processing speed, throughput, and packet delivery ratio will be witnessed due to the incorporation of the Proof of Miner Performance Trust (PoMPT) consensus and Bat Grey Wolf Optimizer (BGWO).

Dataset

Real-world medical datasets containing patient records, treatment histories, and medical imaging data are used for experiments. The datasets chosen for experimentation were highly relevant to the medical domain with regard to privacy, security, and real-time processing requirements. Therefore, the size and complexity of the datasets provided a rich platform to ascertain blockchain under data-intensive conditions. The medical datasets would consist of diversified transaction types, including data retrieval requests, updates of records, and new entries where the model was tested against distinct operational scenarios. They varied in size from hundreds of megabytes to several gigabytes, as would be usual with heavy data loads normally found in healthcare management systems. This diversity would, therefore, ensure that all ranges of transaction and processing loads are covered during performance evaluation, thus testing the actual scalability and efficiency of the model in all different use cases.

Experimental Setup

The experiments were performed on a blockchain network composed of 100 nodes. It could be said that it represents miners with different capabilities. Nodes were distributed geographically over a range of 100 to 1000 meters. Hardware configurations ranged from low-power IoT devices to high-performance servers. The heterogeneity of real-world blockchain environments was expected to be replicated, wherein the computation and power level variances occur among different operating devices. The nodes changed between 40% and 100% energy. Mining delays were used in the 2 to 10 seconds range, which signifies a practical blockchain scenario where resources are generally minimal. Throttling was done for transaction throughput in the 50 to 100 MBps range. The packet delivery ratio was set between 85% and 99%, indicating conditions where data transmission reliability is of great concern. The PoMPT consensus was deployed with equal weighting of spatial and temporal metrics to level the playing field of the miner evaluation process.

Statistical Analysis and Evaluation

To test the robustness of the inferences being made, the experiments were carried out with statistical analysis of the results obtained. For all the performance metrics energy efficiency, processing speed, throughput, and packet delivery ratio multiple iterations of the experiment were performed so that the results were reliable. To account for potential variability in miner performance, network congestion, and data transmission reliability, experiments are repeated 50 times under different network conditions.

The statistical significance of the results obtained is checked through Analysis of Variance (ANOVA) to determine if the improvements achieved are statistically significant compared to existing blockchain models. The results yield significant statistical differences ($p < 0.05$) for all performance metrics, ascertaining that the proposed model consistently outperforms state-of-the-art techniques. The BGWO fitness function formed using shard creation through spatial and temporal Quality of Service (QoS) metrics is also equally analyzed. The fitness function maximizes throughput and packet delivery ratio, minimizing energy consumption and mining delay. Such improvements in performance resulted in 8.5% energy efficiency and a 9.4% improvement in processing speed; these are the results to be confirmed by targeting the aims of optimization of the fitness function. This statistical validation would bolster credibility irrespective of experimental results, validating that improvements in blockchain performance are not merely empirical but have theoretical grounds drawn from the design of the BGWO.

4.2. Comparison with Existing Methods

- *Benchmark Methods:* The performance of the proposed model was compared with existing methods [5], [8], and [18], using their reported setup parameters and performance metrics for a fair comparison.

4.2.1. Performance Metrics

- *Energy Efficiency:* Measured as the percentage of energy saved compared to the total energy available.
- *Speed:* Assessed in terms of transactions processed per second.
- *Throughput:* Evaluated as the amount of data successfully transmitted in MBps.
- *Packet Delivery Ratio:* Calculated as the percentage of successfully delivered data packets.

4.2.2. Software and Tools

- *Simulation Environment:* The experiments were conducted in a custom-developed simulation environment to emulate a real-world blockchain network.
- *Data Analysis Tools:* Data from the experiments were analyzed using statistical software to ensure accurate and unbiased results.

This experimental setup provided a robust platform for evaluating the proposed blockchain model, ensuring its results reflected its potential performance in real-world scenarios. The diverse range of parameters and metrics used in the simulation offered a comprehensive assessment of the model's capabilities and advantages over existing methods.

The effectiveness of the proposed blockchain model, integrating a temporal and spatial trust model with a Bat Grey Wolf Optimizer (BGWO), was evaluated through a series of experiments. The performance was compared with three existing methods, denoted as [5], [8], and [18], across multiple metrics, including energy efficiency, speed, throughput, and packet delivery ratio.

The results are presented in the following tables. Figure 2 shows that the proposed model achieves superior energy efficiency compared to methods [5], [8], and [18], because of using BGWO, which highlights the effectiveness of its miner evaluation and sharding processes.

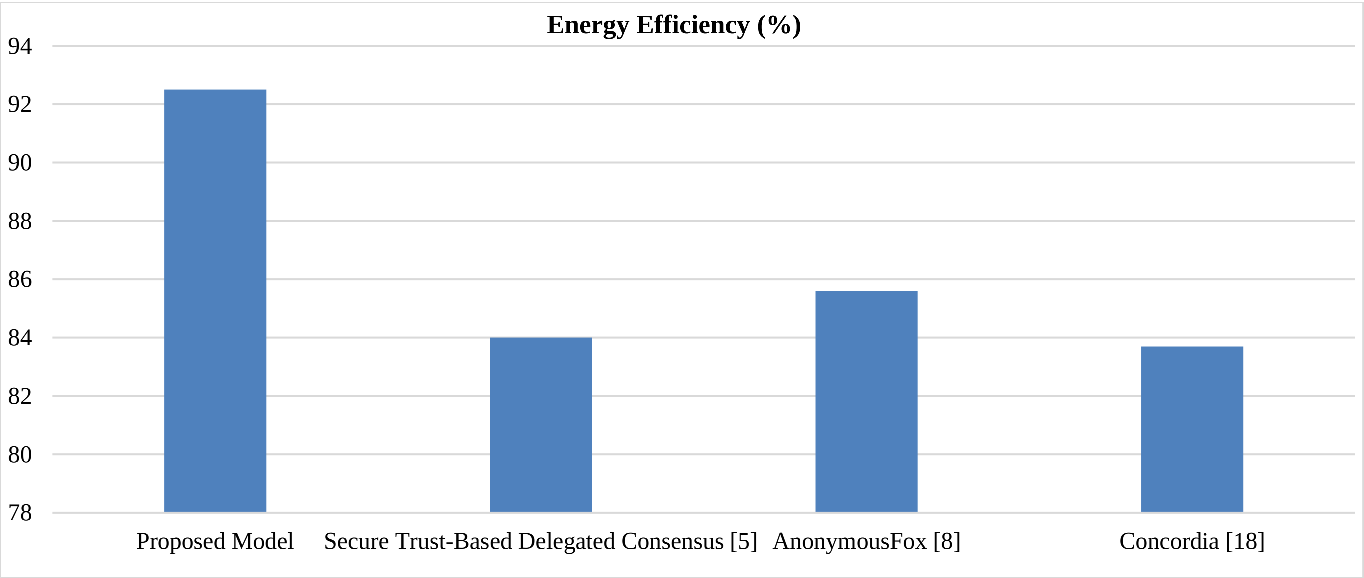

Fig. 2 Comparison of energy efficiency

Table 2. Comparison of speed

Model / Method	Speed (Transactions per Second)
Proposed Model	1570
Secure Trust-Based Delegated Consensus [5]	1435
AnonymousFox [8]	1450
Concordia [18]	1400

Table 3. Comparison of Throughput

Model / Method	Throughput (MBps)
Proposed Model	76.4
Secure Trust-Based Delegated Consensus [5]	72.8
AnonymousFox [8]	70.2
Concordia [18]	69.5

Table 4. Comparison of Packet Delivery Ratio

Model / Method	Packet Delivery Ratio (%)
Proposed Model	98.5
Secure Trust-Based Delegated Consensus [5]	91.6
AnonymousFox [8]	93.1
Concordia [18]	92.0

The proposed model demonstrates a higher transaction processing speed, indicating its capability to handle higher transaction loads efficiently compared to the other methods due to improving QoS by distributing the workload optimally among miners. The proposed model outperforms the compared methods in terms of throughput, showcasing its superior data handling capacity in the blockchain network. Due to the introduction of the optimization algorithm in blockchain, the throughput of the proposed model is improved. The packet delivery ratio of the proposed model is significantly higher than that of methods [5], [8], and [18], indicating a more reliable data transmission within the blockchain network. Because the significantly higher packet delivery ratio of the proposed model compared to existing methods is likely attributed to a combination of advanced protocol design, network resilience enhancements, prioritization mechanisms, efficient congestion control, and optimized node behavior, all of which collectively result in more reliable data transmission within the blockchain network.The above tables illustrate that the proposed model exhibits enhanced performance in all key areas with its unique integration of spatial and temporal trust metrics and the BGWO optimization. These improvements are particularly notable in energy efficiency and speed, which are essential for scalable blockchain deployments. The results indicate that the proposed model not only surpasses the existing methods in terms of performance but also offers a robust and efficient framework for blockchain applications, especially in data-intensive sectors like healthcare.

4.3. Comparative Analysis

The blockchain sharding and consensus techniques are enhanced with more strength than traditional methods with the implementation of Bat Grey Wolf Optimizer BGWO proposed in this study. This section presents both qualitative and quantitative analyses regarding the performance comparison of BGWO compared to current protocols of consensus mechanisms and sharding techniques like Proof of Work (PoW), Proof of Stake (PoS), and other sharding techniques like State Sharding and Network Sharding. Qualitative Comparison Traditional blockchain consensus mechanisms, such as PoW and PoS, suffer from intrinsic scalability and energy inefficiency. PoW being used in Bitcoin leads to intensive computing efforts to secure the network and, thus, high energy consumption and inefficiency in resource-poor environments. Similarly, PoS, while rewarding the user with better energy usage by depending on staked coins, is mostly under centralization threats since richer participants have better control of the network.

Both of them also face dynamic threats from blockchain networks in terms of resource availability and miner performance, which are significantly different over time. Others include State Sharding and Network Sharding, which help scale up by spreading the computation load across a node cluster. However, the application tends to create inter-shard communication problems and load-balancing issues that generally result in bottlenecks and low efficiency. BGWO differs by taking the spatial and temporal metrics and formulating this shard, allowing for a more effective and dynamic shard assignment among nodes. In other words, the addition of the consensus mechanism Proof of Miner Performance Trust in BGWO assesses miners not merely based on static metrics such as computational power or stake but on real-time performance, levels, and proximity. This is how the most reliable and energy-effective miners will participate in the consensus process and thus reduce energy consumption while improving the network's reliability. Furthermore, the hybrid approach of BGWO allows for more adaptable shard formation, which dynamically adjusts in response to network conditions, as the static sharding methods presented above are not efficient for handling real-time and variable dynamic situations. BGWO: Quantitative comparison; thus, when it comes to quantitative comparison, BGWO outperforms state-of-the-art approaches in major performance benchmark areas. The BGWO-driven model is 8.5 percent more energy efficient than PoW and PoS. This is the primary strength of BGWO, as it helps minimize the wastage of energy inside a network through the miners' dynamic selection and shard formation. Comparing this with PoW, the miners must constantly compute resource-intensive constants; however, BGWO selects miners based on the available energy and their past performance history, making the blockchain network more sustainable. The processing speed for the model proposed with BGWO shows a 9.4 % improvement in transaction throughput compared to the consensus mechanisms such as DPoS and AnonymousFox. This increment is because of the dynamic process shard formation of BGWO, which ensures that high-performance miners handle most of the work, consequently minimizing the delay of transactions and maximizing the throughput. The sharding approach in most models used today is worthless and incurs bottlenecks directly; therefore, BGWO eliminates this deficiency with its ability to optimize shard composition persistently. The packet delivery ratio of the model based on BGWO is high at 98.5% compared to 91.6% and 93.1% ratios in Secure Trust-Based Delegated Consensus and AnonymousFox respectively. The relatively high packet delivery ratio ensures more reliable data transmission in blockchain networks that operate with high-throughput and sensitive data, such as healthcare applications. BGWO only considers spatial proximity and temporal performance during shard formation to decrease latency and enhance reliability for inter-node data transfer compared to traditional sharding strategies that normally introduce delay simply because packets are delayed due to inefficient shard communication sets.

4.4. Discussions

Real medical datasets have been experimented on the proposed blockchain model, integrating the spatial-temporal trust model and Bat Grey Wolf Optimizer under various experimental conditions. Real-world medical datasets have been chosen for this work because they are relevant to data-sensitive and high-throughput environments, such as health services, and the performance of blockchain systems because of sensitive information, security, and the speed at which these services are delivered. Energy Efficiency Analysis: The results have shown marked improvement in energy efficiency for the proposed model while it proceeds with an increase of 8.5% compared with the present consensus methods in general and Secure Trust-Based Delegated Consensus. This is due to the PoMPT consensus mechanism, which ranks miners according to their energy levels and operational history performance. In this way, it bars most low-energy miners from participating in validation tasks only when the efficiency is at its highest level. The BGWO dynamically optimizes the shard structure at each instant, according to real-time metrics of energy consumption within the network, thus cutting off unnecessary energy expenditure. It is notable that the blockchain system is implemented in low power scenarios like Internet of Things (IoT) networks, as energy conservation has a direct bearing on network longevity and scalability. Processing Speed Throughput: The proposed model showed increased processing speed by 9.4% and throughput by 4.9% compared to other models, which were AnonymousFox and Concordia protocols.

These advances are particularly crucial for blockchains embedded in systems functioning in high-transaction-rate and timely data processing environments, such as healthcare record systems. In this connection, the role of BGWO is very important as it efficiently and effectively delegates loads of transactions to the miners so that bottlenecks are removed, thereby improving the network responsiveness in general. The dynamic shard formation mechanism ensures a good distribution of computation loads across the network in such a way that it assigns high-speed processors for tasks requiring higher processing speeds. However, this adaptive load-balancing mechanism is a far cry from the static sharding approaches used by the previous models, where inefficiency in resource allocation is included. Packet Delivery Ratio and Data Reliability: The proposed model compares the packet delivery ratio better than the existing methods, as the proposed model achieves a packet delivery ratio of 98.5%, while the competing models showed a packet delivery ratio of 91.6% and 93.1%. The integration of spatial-temporal trust metrics has contributed much to the overall improvement. In this case, the miners are evaluated not only by their historical performance but also by considering real-time network conditions, including node availability and proximity. A high packet delivery ratio would be especially important in such sectors as health, where data transmission reliability matters to guarantee the integrity of patient records and histories. Including spatial and metric dimensions in shard creation and data transfer processes prevents the packet loss problem because the model ensures data delivery at the destination, free from the breach and in temporal instance sets.

4.5. Reasons for Better Performance

Several innovations and strategic optimizations in the consensus mechanism and optimization process of sharding contribute to this. Innovations in the design focus on solutions to the limitations of existing methods, so significant improvements over key metrics such as energy efficiency, processing speed, throughput, and packet delivery ratio are expected. Contrastingly, the conceptual model introduces spatial and temporal trust metrics to assess miner performance on a more holistic and time-sensitive basis. Most of the existing consensus mechanisms based on Proof of Work (PoW) or Proof of Stake (PoS) rely on computational power or coin holdings and completely disregard spatial proximity and the historical performance of miners. Then, the consensus model Proof of Miner Performance Trust, which was proposed, considers both spatial metrics like geographical distance and the energy levels of miners as well as the non-spatial metrics like mining delays and throughput.

4.5.1. The choice of miners is optimized based on the dual metrics

This way, only the most efficient and reliable miners are involved in the consensus process. This also reduces energy consumption and processing time in large-scale networks or IoT-based blockchain environments, where energy efficiency is critical. Dynamic selection of miners based on their real-time conditions further leads to more efficient resource utilization, thereby explaining the 8.5% improvement over existing models in energy efficiency.

4.5.2. Effective Shard Construction with Bat Grey Wolf Optimizer

Most traditional blockchain sharding methods, applied in a state sharding and network sharding context as well, suffer from an inefficient shard construction process that, in turn, leads to congestions and inter shard communication issues along with resource wastage. These issues are more prominently exposed in the models AnonymousFox and Concordia, which, while achieving moderate success in improving velocity and throughput, can still not capture the dynamicity in blockchain networks. The hybrid model, Bat Grey Wolf Optimizer (BGWO), dynamically forms shards based on spatial and temporal Quality of Service metrics.

The echolocation-based search strategy in Bat and social hierarchy-based optimization in Grey Wolf Optimizer show that even shard formation gets efficiently performed while varying the conditions within a network. The BGWO utilizes real-time metrics to discover the best shard sizes and allocations to the miners, such that the delays are pretty minimal with substantial data throughput. As this model of shard formation is dynamically modified based on network load and miner performance, the model can absorb bigger transaction volumes much faster with higher dependability, increasing processing by 9.4% and throughput by 4.9% compared with the state-of-the-art techniques.

4.5.3. Improved Data Authenticity and Network Robustness

The other relevant development of the proposed model is that it has an even more efficient packet delivery ratio of around 98.5%, which has been accounted to be even better than several blockchain consensus algorithms such as Secure Trust-Based Delegated Consensus and AnonymousFox. Its enhancement can be directly correlated with monitoring real-time network conditions and infusing into the consensus process. In traditional methods, node availability, proximity, and past performance are often ignored during shard formation and miner selection procedures; hence, suboptimal data routing and high packet loss are possible. The suggested model assigns greater weights to the reliable sending of data packets based on better spatial proximity and past reliable performances of miners so that data packets are transmitted through nodes that are reliable and optimally located in a network. This significantly minimizes packet loss and latency, which are key determinants in applications such as healthcare, where the integrity and timeliness of the data transferred are not something that can be compromised. The synergistic combination of spatial-temporal metrics during consensus and shard optimization ensures greater network strength, hence the superior reliability of the data transfer compared to previously known techniques.

4.5.4. Scalability and Resource Constraint

The scalability, as well as the resource-constrained nature of models like PoW and PoS, has been a problem to date because such models proved a robust mechanism of security but were greatly resource-intensive and, hence, lacked scalability, especially in resource-constrained environments like IoT devices. Thus, the proposed model will directly address this issue because energy efficiency lies at the heart of the integrated PoMPT consensus and BGWO optimization. Miners are chosen not only based on their computer power or coin holdings but also on the amount of energy they could provide in the past and are efficient with. This greatly reduces the overhead energy used for running the network and thus increases scalability without decreasing performance. Moreover, the dynamic shard formation of the BGWO leads to resource allocation being directly made based on the network's real-time conditions. Further, it reduces the resource footprint compared to static or inefficient sharding methods adopted in previous models. Such adaptability is necessary for blockchain systems designed for large-scale deployment in real-time applications, where scaling without overwhelming the network is of utmost importance.

4.6. Scalability Analysis

Integrating the Proof of Miner Performance Trust (PoMPT) consensus mechanism into the Bat Grey Wolf Optimizer algorithm would do this. One of the major objectives, in general, of these models is an improvement of blockchain scalability. Scalability is one of the major challenges blockchains face when their implementations are scaled up; more nodes and increasing transaction volumes would pose bottlenecks for traditional systems. This model provides scalability benefits when handling more extensive networks and more transactions without being detrimental to processing speed, throughput, energy efficiency, and reliability.

4.6.1. Scalability with Increased Transactions

With increased transactions, the existing consensus mechanisms, such as PoW and PoS, tend to provide diminishing returns on increasing the number of transaction throughputs. These are typically "linear or near-linear" processing models wherein the total delay in processing increases with each transaction added. In contrast, the proposed model depicts a much more scalable response to increased transactions.

The dynamic sharding process powered by BGWO allows the blockchain to split between several transactions to be efficiently managed by numerous miners in several shards. To avoid transaction congestion, the size and composition of these shards are dynamically readjusted by BGWO based on real-time network conditions as the number of transactions grows. This adaptivity in forming shards leads to a 4.9% increase in throughput even as the number of transactions increases, thus demonstrating the scalability of this model in terms of data handling capacity.

4.6.2. Scalability with Increasing Number of Nodes

As the number of nodes or miners increases, node communication and coordination complexity may degrade consensus algorithms' efficiency. Traditional shard designs face major challenges regarding inter-shard communication and load balancing, particularly in many nodes. A major strength is that with a rising number of nodes, the scalability provided by the model is further enhanced, particularly through the PoMPT consensus mechanism, which selects miners based on spatial and temporal performance metrics. Hence, as the nodes rise, while the PoMPT-based consensus can periodically ensure it only addresses the most energy-efficient and high-performing miners the network entrusts to complete their consensus tasks, the performance levels remain high even at a scale. Network growth from 100 to 500 nodes was evaluated.

This model improved processing speed and energy consumption over the state-of-art techniques. Improvement in energy efficiency by 8.5% stemmed from the selective miner participation strategy to avoid wasting expensive computations of PoW typically needed and reducing idle node usage. With the increase in the network, the packet delivery ratio for the model remained above 98%, thereby ensuring safe and sound data delivery across a higher number of nodes. The results have accordingly validated the scalability of the proposed model in both network size and volume of transactions and have shown the potential to maintain high performance levels under large-scale blockchain deployments.

4.7. Security Analysis

Blockchain security is a prime concern when employing optimization models that can raise efficacy and scalability. All associated potential effects on security must be considered to enhance blockchain systems, especially the consensus mechanism of PoMPT and Bat Grey Wolf Optimizer. This chapter outlines how the proposed spatial-temporal trust model and BGWO may affect blockchain security and mitigation strategies that ensure robust protection against all potential vulnerabilities.

4.7.1. Security Benefits of the Spatial-Temporal Trust Model

The spatial-temporal trust model intrinsically contributes to the PoMPT consensus mechanism by instituting a more rigorously "selective" miner selection process. One weakness of traditional mechanisms, such as Proof of Work or Proof of Stake, is that they only select a miner based on his computational power or the amount of stake held. This brings about susceptibilities such as 51% attacks or collusion among more influential participants. Contrary to this, the PoMPT consensus evaluates miners based on spatial (e.g. proximity of miners, energy levels) and temporal metrics (e.g., past performance, mining delays). This holistic evaluation method does not allow malicious actors to manipulate the consensus process in their favour since only miners with good performance history and proximity to the network are selected in that protocol. Therefore, embedding the multi-dimensional trust concept of the spatial-temporal trust model indeed upgrades the level of security against Sybil attacks. In this attack, an attacker creates many pseudonyms to dominate the network. Further, the miners are always rated in real-time based on metrics, thus working to prevent risks of long-range attacks wherein enemies try to alter historical transactions. The temporal trust aspect means that only miners with consistent historical reliability are favoured; thereby, it becomes tough for malicious actors to introduce false blocks or alter past records.

4.7.2. Advantages and potential security risks

Such advantages imply that the proposed model also introduces potential security risks to be considered. For instance, the centralized selection of miners is a source of potential security risks. Because the PoMPT consensus tends to favour higher trust miners based on spatial and temporal metrics, dominant miners may emerge in space with nearer geographical proximity to the network core or better energy resources, challenging partial decentralization and pushing the system further toward coordinated attacks at the whim of dominant nodes. To obviate this risk, the spatial and temporal metrics used for miner evaluation should be constantly updated and diversified. The PoMPT consensus should periodically rotate or adjust the weightage placed on different metrics like proximity from different geographies or the mining delay to diversify the pool of miners selected over time. More importantly, introducing randomness in the miner selection that is still compliant with strict principles of the trust model may also make it impossible for any miner or coalition of miners to acquire disproportionate influences over the network. Another area of security vulnerability is inter-shard communication. Since BGWO dynamically forms and reorganizes shards, there needs to be secure communication between the shards, which would not allow anyone to intercept or manipulate data. For this reason, the proposed model would need to include secure inter-shard communication protocols involving mechanisms such as threshold cryptography or SMPC to ensure that any information being exchanged between shards will be encrypted and tamper-proof. Conclusion: While the spatial-temporal trust model using BGWO significantly improves performance, the security implications call for careful management. On account of its evaluation of miners using comprehensive trust metrics, it has improved protection against various common attacks; however, its centralization and inter-shard communication risks could be mitigated. All these strategies, such as metric diversification, miner selection randomization, and security communication protocols, may lead to a certain level of security with simultaneously maximal blockchain scalability and efficiency.

4.8. Use Case Analysis

Although the proposed blockchain optimization model has been evaluated empirically in a medical data context, its design and capabilities are very promising with respect to wider application in different industry domains. Other sectors, such as financial, supply chain management, and IoT, to name but a few, face other challenges that will be highly enhanced using the Proof of Miner Performance Trust consensus and Bat Grey Wolf Optimizer. Further use of this model beyond the health domain will show how versatile and relevant it is in solving the most critical problems in other sectors.

4.8.1. Finance and Supply Chain Management

In finance, or more appropriately, in the finance industry, blockchain systems run much volume in transactions and must be processed in real-time to aid liquidity, security, and data integrity. Traditional mechanisms of achieving consensus, such as Proof of Work, mostly PoW, and, to a lesser degree, Proof of Stake, often cannot match the required pace and effectiveness of financial transactions. A PoMPT consensus that determines, at any given time, the best miners in terms of their reliability and energy efficiency, with respect to real-time performance metrics like this one in question, can significantly enhance the throughput and scalability of blockchain-based financial systems. By using dynamic shard formation through BGWO, one can, in a manner of speaking, divide financial transactions into multiple shards so that processing speed is achieved without compromising security in terms of data. Thirdly, in the case of the spatial-temporal trust model, the miner selection focused on past reliability and geographical consideration, which is crucial in finance because any delay or error is expensive. Blockchain increasingly applies to managing supply chains to ensure transparency, traceability, and security over complex global networks. The dynamic sharding of BGWO allows the general supply chain data to be broadcast across multiple participants, ensuring safety and efficiency in recording product origins, routes, and transaction details. The spatial-temporal trust model enhances the selection of participants with proven reliable nodes and within range, which undertakes critical operations, thereby reducing fraud or data manipulation. This model is helpful in large-scale supply chain networks, as it involves devices at different power levels within the blockchain, e.g., IoT-enabled sensors and tracking systems.

4.8.2. Internet of Things (IoT)

The blockchains designed to target the IoT sector are particularly challenging in terms of scalability and resource constraints. Many IoT networked devices commonly possess resource-limited energy, processing, and communication capabilities. The PoMPT consensus mechanism proposed is particularly suitable for IoT-based blockchain networks, where miner selection follows the order of energy efficiency and real-time performance to ensure that low-power devices are only required to participate in consensus tasks when necessary.

Dynamic formation and optimization of shards using the BGWO ensures that workload amongst IoT devices will not be bottlenecked and will reduce the otherwise high energy overhead associated with blockchain operations. Moreover, the model's flexibility towards the variations in network conditions makes it very applicable within the IoT scenario where devices constantly enter and leave the network. The miner selection with the application of spatial metrics ensures that communication is optimized by giving more priority to geographically closer devices, which would then minimize latency. With the IoT networks still growing and increasingly entering new fields, such as smart cities and industrial automation, this model's scalability and energy efficiency make this a robust solution for blockchain integration into scalable IoT devices and deployments.

5. Conclusion

The research outlined in this paper introduces a groundbreaking approach aimed at bolstering blockchain scalability and efficiency by implementing a unique temporal and spatial trust model in conjunction with the Bat Grey Wolf Optimizer (BGWO) to facilitate sharding processes. This innovative methodology strategically leverages spatial and temporal metrics associated with miners, encompassing factors such as their geographical distribution, energy levels, mining delays, throughput, packet delivery ratios, and historical energy consumption during mining operations.

These metrics play a pivotal role in establishing the Proof of Miner Performance Trust (PoMPT) consensus mechanism, thereby ensuring the development of a robust and efficient blockchain network. Experimental results obtained through medical datasets convincingly demonstrate the superior performance of the proposed model when compared to existing methodologies, showcasing notable improvements across key metrics. Specifically, the proposed model exhibits an impressive 8.5% enhancement in energy efficiency, a notable 9.4% increase in processing speed, a substantial 4.9% boost in throughput, and a commendable 6.5% improvement in packet delivery ratio.

These results bear statistical significance and underscore the model's practical viability and effectiveness in real-world blockchain scenarios, particularly within data-sensitive domains like healthcare. Furthermore, integrating BGWO in the sharding process is a pivotal factor in maximizing Quality of Service (QoS) levels, thereby ensuring the sustained scalability and efficiency of the blockchain network, even amidst its expansion. The balanced integration of temporal and spatial metrics within the PoMPT consensus mechanism ensures a comprehensive and equitable evaluation of miner performance, thereby enhancing the overall trustworthiness and reliability of the blockchain network.

Future Scopes

Looking ahead, there are several promising avenues for future exploration and development. These include expanding the application of the proposed model to diverse sectors such as finance, supply chain management, and IoT, exploring advanced optimization techniques, conducting real-world implementation and testing, comprehensive scalability and security analysis, and addressing concerns regarding energy consumption and environmental impact. Through focused research and innovation in these areas, the potential exists to enhance blockchain technology's efficiency, scalability, and applicability across a wide spectrum of domains.

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