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Queueing Theory in Blockchain-AI Integrated Systems

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Abstract---The integration of blockchain and artificial intelligence (AI) systems introduces new challenges in managing latency, scalability, and resource allocation within decentralized environments. This paper proposes a mathematical framework based on queueing theory to model and analyze the performance of blockchain-AI integrated systems. In particular, we represent transaction validation, data propagation, and AI task execution as interconnected stochastic service systems, capturing their dynamic and probabilistic behavior. We develop a multi-class queueing model in which blockchain transactions and AI computational tasks compete for shared network and processing resources. Using Markovian and non-Markovian queue structures, we derive key performance metrics including average waiting time, system throughput, queue stability conditions, and service efficiency under varying load conditions. The model incorporates consensus delays, block generation intervals, and AI training or inference times as stochastic processes. Furthermore, we investigate optimization strategies using priority scheduling and load balancing mechanisms to improve system performance. Analytical results are validated through simulations, demonstrating how queueing-based optimization can reduce latency and enhance scalability in decentralized AI applications such as federated learning and smart contract automation. The proposed framework provides a rigorous mathematical foundation for understanding and optimizing blockchain-AI ecosystems, offering insights into the design of efficient, scalable, and reliable decentralized intelligent systems.

Keywords---Queueing Theory, Blockchain, Artificial Intelligence, Stochastic Modeling, Performance Analysis, Latency, Distributed Systems

I INTRODUCTION

The rapid advancement of blockchain technology and artificial intelligence (AI) has led to the emergence of decentralized intelligent systems that combine secure data management with autonomous decision-making capabilities. Blockchain provides a distributed, tamper-resistant ledger that ensures transparency, trust, and immutability, while AI enables data-driven learning, prediction, and automation. The integration of these two technologies has gained significant attention in applications such as federated learning, smart contract automation, healthcare systems, and financial services. Despite its potential, the convergence of blockchain and AI introduces substantial challenges related to latency, scalability, and resource allocation. Blockchain networks often suffer from limited throughput and high transaction confirmation delays due to consensus mechanisms and block generation constraints. At the same time, AI workloads—particularly training and inference tasks—are computationally intensive and exhibit dynamic, bursty arrival patterns. When these processes coexist in a shared decentralized environment, they compete for limited computational and communication resources, leading to congestion and performance degradation.

To address these challenges, queueing theory provides a powerful mathematical framework for modeling and analyzing systems characterized by stochastic arrivals and service processes. By representing blockchain transactions, data propagation, and AI tasks as queueing systems, it becomes possible to capture the probabilistic behavior of delays, waiting times, and resource utilization. Queueing models such as M/M/1, M/G/1, and multi-class systems enable the evaluation of system performance under varying workloads and network conditions.

In this paper, we propose a queueing-theoretic framework for analyzing blockchain–AI integrated systems. The proposed model considers both transaction processing and AI computational tasks as interconnected service queues, incorporating key system characteristics such as consensus delays, block generation intervals, and heterogeneous service times. Furthermore, we explore optimization strategies such as priority-based scheduling and load balancing to improve system efficiency and reduce latency. Analytical findings are supported by simulation results, demonstrating the effectiveness of queueing-based approaches in enhancing the performance of decentralized AI applications.

The main contributions of this work are summarized as follows:

- Development of a unified queueing-theoretic model for blockchain–AI systems
- Analytical derivation of key performance metrics under stochastic conditions
- Investigation of scheduling and resource allocation strategies

The remainder of this paper is organized as follows. Section II Queueing Theory. Section III presents the

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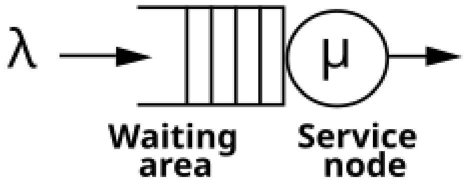
Model Description for a Blockchain Queue. Section IV provides Synergies Between AI And Blockchain. Section V discusses Applications of Blockchain in AI. followed by conclusions in Section VI.

II QUEUEING THEORY

Queuing Theory Parameters	
Arrival	Refers to the customers who arrive and are first in line
Queue or Service Capacity	Refers to the limits of the system as per the number of customers in line
Number of Servers	Refers to the total number of employees serving the customers in line
Size of the Client Population	Refers to the total number of customers in line
Queuing Discipline	Refers to how requests are delivered to the servers (includes first-in, first-out)
Departure Process	Refers to customers leaving after receiving service



III MODEL DESCRIPTION FOR A BLOCKCHAIN QUEUE

In this section, based on the real background of blockchain, we design an interesting blockchain queue, in which the block-generation and blockchain-building processes are expressed by means of a two stages of batch services.

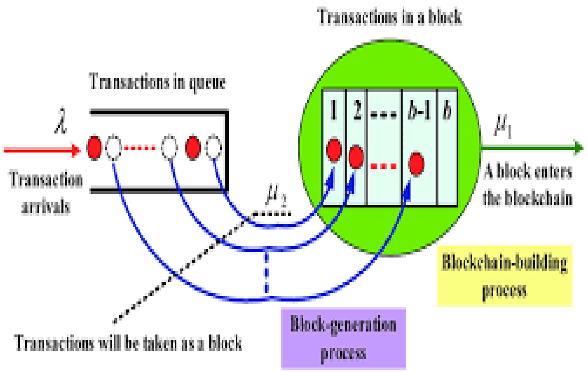


Fig.1.A Blockchain queueing System

Arrival process: Transactions arrive at the blockchain system according to

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Arrival process: Transactions arrive at the blockchain system according to a Poisson process with arrival rate λ. Each transaction must first enter and queue at an waiting room of infinite size. Note that the arrival process of transactions is denoted in the left part of Figure 1.

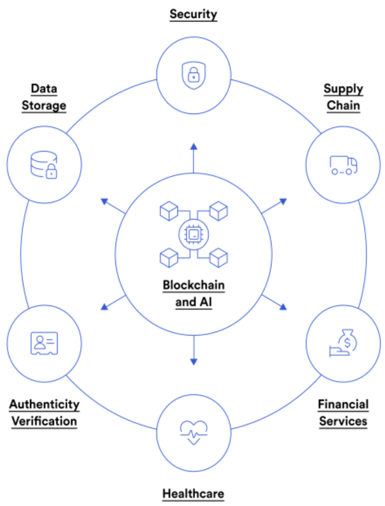
Service process: Each arrival transaction first queues up in the waiting

Service process: Each arrival transaction first queues up in the waiting room. Then it waits for being successfully mined as a block, this is regarded as the first stage of service, called block generation. Finally, the block with this transaction is built into the blockchain, this is regarded as the second stage of service, called blockchain building, see the right part of Figure 1.

In the blockchain system, we assume that the block-generation times in the first stage are i.i.d and exponential with service rate μ2; the blockchain-building times in the second stage are i.i.d and exponential with the service rate μ1. Maximum block size: To avoid the spam attack, the maximum block size

Maximum block size: To avoid the spam attack, the maximum block size is limited. We assume that there are at most b transactions in each block. If the resulting block size is smaller than the maximum block size b, then the transactions newly arriving during the mining process of a block can be accepted in the block again. If there are more than b transactions in the waiting room, then we assume that a new block will include b transactions through the full blocks to maximize the batch service ability in the block chain system.

1. **Waiting Time:** Time a transaction waits in the pool.
2. **Service Time:** Time required to mine a block and achieve consensus.
3. **Queue Length:** Total pending transactions a waiting processing.



IV SYNERGIES BETWEEN AI AND BLOCKCHAIN

Blockchain Enhancing AI

1.Data Provenance and Integrity: Blockchain ensures the data fed into AI models is untampered, reliable, and authentic, reducing data bias or corruption.

2.Decentralized Training: Blockchain facilitates collaborative AI development (federated learning) where

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models are trained locally, ensuring sensitive data remains private while sharing insights on the ledger.

3.Verifiable AI Decisions: AI decisions can be immutably logged on a blockchain, providing a transparent, auditable trail.

AI Enhancing Blockchain:

- **Smart Contract Security and Intelligence:** AI audits smart contracts for code errors, security flaws, and vulnerabilities before deployment.
- **Network Optimization and Scalability:** AI algorithms analyze network traffic to optimize resource usage and improve throughput.
- **Anomaly Detection / Security:**
  AI continuously monitors transactions for fraud, identifying suspicious patterns and preventing malicious attacks on decentralized ledgers.

V APPLICATIONS OF BLOCKCHAIN IN AI

Queueing Theory plays an important role in understanding and optimizing how **transactions are processed in blockchain systems**. Since blockchains naturally involve waiting lines (transactions waiting to be confirmed), concepts from Queueing Theory help model and improve their performance.

Transaction Processing & Confirmation Time: Queueing theory is used to model the "memory pool" (mempool) of a blockchain, where transactions wait for confirmation. By modeling the arrival rate and service rate of miners, the theory helps estimate the time required for a transaction to be included in a block.

Optimal Resource Allocation (AI-Driven): AI can be used to predict traffic surges, and queueing models are then employed to calculate the optimal number of servers or nodes to engage to handle the load, preventing bottlenecks. This is particularly critical in IoT-based blockchain systems where devices send data at different rates.

Consensus Mechanism Optimization:
Models such as M/PH/1 are applied to evaluate consensus mechanisms like Delegated Proof of Stake (DPoS) and Practical Byzantine Fault Tolerant (PBFT). It helps to determine the stability conditions of the consensus process, ensuring that the time of block verification is minimized.

Smart Contract Execution: Queueing models analyze the waiting lines for smart contract execution, optimizing for high-priority vs. low-priority service requests.

Two-Stage Mining Process Analysis: Research utilizes a "Markovian-batch-service" queueing framework to model the two stages of mining: block-generation (first stage) and blockchain-building (second stage).

VI CONCLUSION

Queueing Theory provides a powerful mathematical framework to analyze and manage the flow of transactions, data, and computational tasks in blockchain networks. When integrated with AI, it transforms from a passive analytical tool into an **intelligent, adaptive system** capable of predicting congestion, optimizing transaction scheduling, dynamically adjusting fees, and improving resource allocation. This synergy enhances blockchain performance by reducing latency, increasing throughput, and ensuring system stability, while also enabling smarter decision-making in decentralized networks.

REFERENCES

[1] Li, Q.-L., Ma, J.-Y., & Chang, Y.-X. (2018). Blockchain queueing theory. arXiv.

[2] Memon, R. A., Li, J. P., & Ahmed, J. (2019). Simulation model for blockchain systems using queuing theory. Electronics.

[3] Ricci, S., Ziviani, A., Ferreira, E., Souza, J. E. S., Menasché, D. S., & Vieira, A. B. (2019). Learning blockchain delays: A queueing theory approach. Performance Evaluation Review.

[4] Siddiqui, S., Fatima, S., Ali, A., Gupta, S. K., Singh, H. K., & Kim, S. (2025). Modelling of queuing systems using blockchain based on Markov process. Scientific Reports.

[5] Kawase & Kasahara, (2017). Transaction-Confirmation Time for Bitcoin: A Queueing Analytical Approach to Blockchain Mechanism