# Introduction

Blockchain technology, first proposed by Nakamoto in 2008, has rapidly evolved into a foundational infrastructure for digital trust and decentralized systems. As a form of distributed ledger technology (DLT), blockchain is characterized by decentralization, transparency, and immutability, making it particularly suited for secure data storage and peer-to-peer value transfer. Each block contains a hash of the previous block, a timestamp, and a collection of transactions, forming an append-only chain that is nearly impossible to tamper with. Originally designed to support cryptocurrencies like Bitcoin, blockchain has since been adopted in numerous domains including finance, healthcare, media, logistics, and energy.

One of the most pressing technical challenges in today’s blockchain landscape is interoperability, that is the ability for independently operated blockchain networks to communicate and exchange assets or information. This challenge has spurred the development of cross-chain bridges, which act not as physical connections but rather as a collection of protocols and mechanisms that allow heterogeneous blockchains to interoperate. These bridges enable asset transfers, data exchange, and coordinated smart contract execution between public chains, consortium chains, and private chains, which are otherwise isolated due to architectural and consensus differences. Similar concerns have also emerged in layered edge-cloud systems, where performance evaluation frameworks are often built on queueing-theoretic modeling.

To address the performance analysis of blockchain systems, a number of prior works have employed queueing theory to model system dynamics under realistic assumptions. For instance, researchers have simulated edge-cloud offloading networks using M/G/1 and M/G/m models to assess task delays and system throughput in blockchain-based layered environments [1]. Another study applied M/M/n/L queues to model transaction processing and block generation in Bitcoin, demonstrating how queue length and block production rates impact performance [2].

In more structured systems such as Hyperledger Fabric, a queueing network model was proposed to divide the consensus process into execution, ordering, and validation stages, enabling analysis of latency across phases [3]. Other researchers combined queueing models with multidimensional Markov chains to analyze PBFT-based consensus systems with repairable voting nodes, quantifying system reliability and throughput under dynamic conditions [4]. Performance bottlenecks in Fabric’s architecture were also identified via benchmarking, helping guide practical optimizations [5].

Beyond consensus mechanics, theoretical models have captured the growth dynamics and reward allocation strategies in multi-mining pool environments such as Ethereum. One study introduced a tree-based blockchain structure and renewal reward theory to model stale and uncle blocks [6]. Priority-based transaction handling has also been modeled using non-preemptive limited-priority queues, illustrating the performance tradeoffs between high- and low-priority transaction classes [7]. To tackle intractable steady-state distributions in complex systems, another approach applied the maximum entropy principle to estimate probabilities based on observable statistics, providing flexible approximations without strong distributional assumptions [8].

In response to the lack of simple yet effective models for analyzing cross-chain systems, this thesis draws on examples from [9] and [10] to develop a queueing model for cross-chain transaction flows. The model abstracts the system into two sequential queues: the customer queue, where transactions wait to be selected for block formation, and the block queue, where blocks undergo consensus. To better capture realistic customer behavior, the model considers multiple user classes with non-preemptive limited priority and partial batch service, as well as channel states that alternate between ON and OFF. User impatience is also incorporated to reflect transaction abandonment in highly congested environments. These dynamics are analyzed across four scenarios: (1) single-class customers without impatience, (2) two-class customers without impatience, (3) single-class customers with impatience, and (4) two-class customers with impatience.

To evaluate the system's steady-state behavior under complex configurations, this thesis adopts a numerical iteration method based on the balance equations of the underlying Markov chain. A simulation is also performed for validation. This approach enables the computation of key performance metrics.

This thesis proceeds as follows. Chapter 2 introduces the system model, detailing the cross-chain process structure and the queuing assumptions used in this study. Chapter 3 presents the analytical model, which formalizes the system behavior under various parameter settings and derives key performance metrics. Chapter 4 describes the simulation model, providing implementation details and simulation strategies used to validate the analytical results. Chapter 5 reports the numerical results and performance evaluation across the proposed scenarios. Finally, Chapter 6 concludes the thesis and outlines potential directions for future work.