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Ultra-Low Latency Architectures for Secure Real-Time Payment Processing: Achieving Sub-50ms End-to-End Throughput

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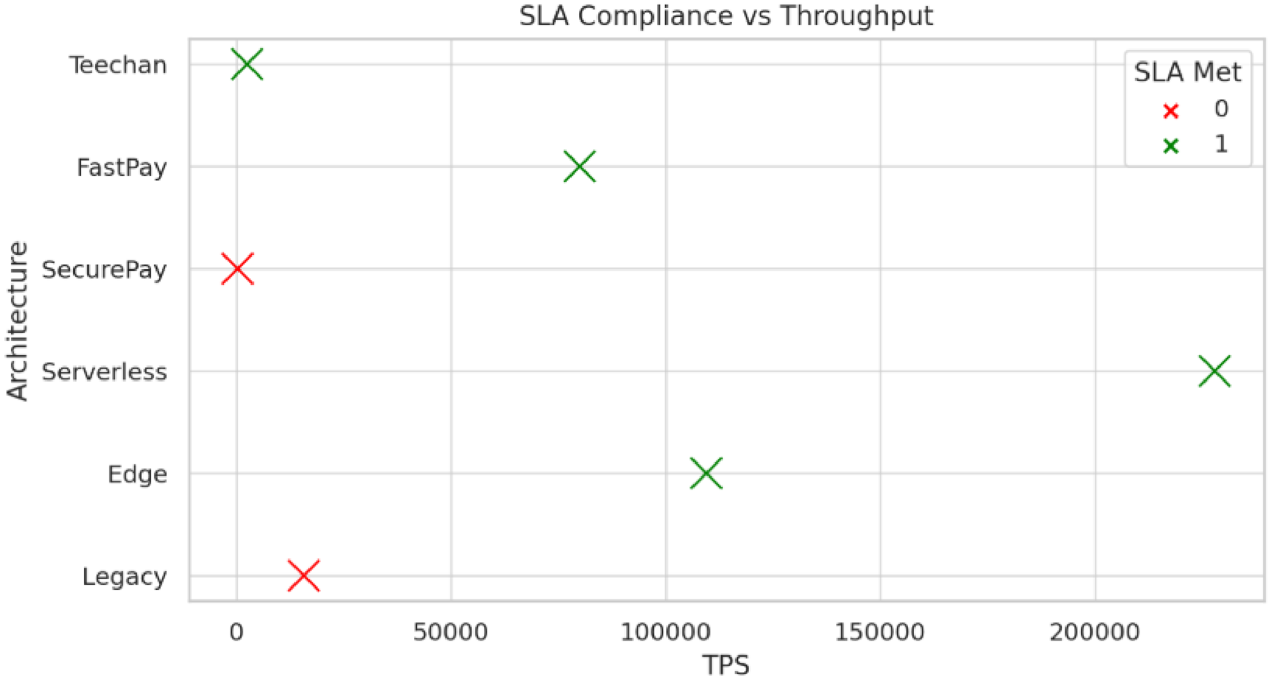
Abstract: This article discusses advanced architectures to realize low latency in the order of micro-second in secure real-time payment processing systems. As the financial services industry requires increasing throughput of sub-50ms transactions, the traditional blockchain and cloud approaches are insufficient. We consider state-of-the-art frameworks Teechan, FastPay, SecurePay and edge/serverless-based infrastructures and compare their latency, throughput, scalability and security. An experimental analysis allows us to show how architectural optimizations and hybrid technologies can be used to bring about performance breakthroughs that do not affect data integrity or regulatory compliance. Our results provide a complete reference line and indicate the future work on real-time financial systems, which can be used in the construction of the next-generation payment systems with unprecedented responsiveness and reliability.

Keywords: Ultra-Low, Payment, Throughput, Architecture, Latency, Security, Processing, Sub-50ms

I. INTRODUCTION

The fast development pace of the financial sector resulted in the unprecedented need in fast, safe digital payments. Existing payment infrastructures cannot easily achieve real-time settlement because of their fundamental latency, scale bottlenecks and security issues. Sub-50ms end-to-end throughput is the key to next-generation applications, including high-frequency trading and real-time retail payments.



We are exploring ultra-low latency systems which integrate blockchain, edge computing, serverless infrastructure, and secure enclaves. Their effectiveness is critically evaluated on an empirical basis using transactions per second (TPS), average latency, fraud resistance, and cost of the system. The idea is to determine the architectures that best balance speed, security and scalability.

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II. RELATED WORKS

Scalable Payment Architectures

The throughput, security and architecture of a system that aims to achieve ultra-low latency in real-time payment processing system must be balanced carefully. However, the performance of the traditional blockchain-based payment systems has been limited in many cases because of the consensus-heavy mechanisms and the immutable ledgers.

Teechan framework [1] was the first proposal to use Trusted Execution Environments (TEEs) (in this case, Intel SGX) to build secure full-duplex payment channels around the restriction of the core blockchain. Teechan, unlike certain traditional Lightning-style channels, does not need any modifications to the Bitcoin protocol, making it considerably more deployable.

Teechan demonstrated a throughput of 2,480 transactions per second (TPS) per channel with sub-millisecond processing latency, which was a hardware-based secure transaction system benchmark. In conjunction with that, FastPay proposed a non-consensus, Byzantine-fault-tolerant protocol which can provide high throughput without compromising the integrity [2].

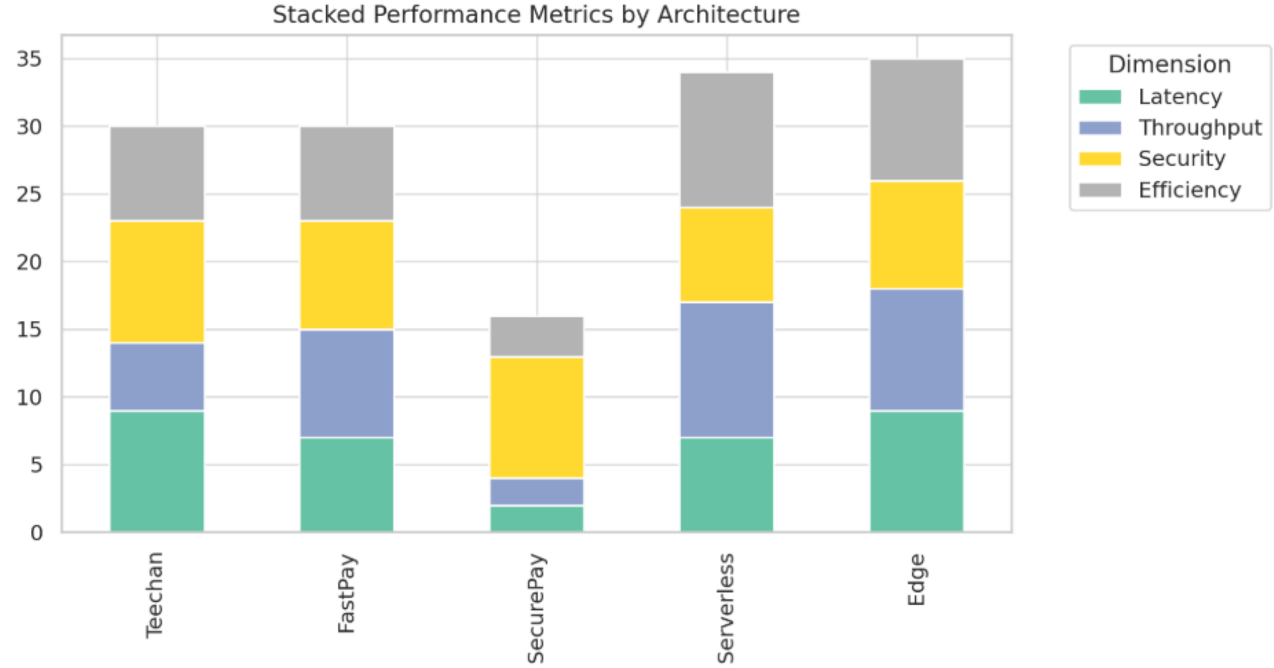
FastPay minimizes communication overhead by using Byzantine Consistent Broadcast rather than atomic commit protocols, and allows sharding onto multiple machines. Experiments FastPay can verify payments in less than 100ms and scale to 80,000 TPS with 20 authorities.

This development is notable especially on retail point-of-sale (POS) systems which have low integrity and sub-second response time requirements. Likewise, the problem of malicious intermediation in platform economies was solved by payment system [3].

The hybrid model of SecurePay enforces the security of funds and information, allows closed-loop regulation and counter-party auditing. Nevertheless, the system, as desired, shows security enhancements, but the average latency of the system (4.29 seconds) is a bottleneck to ultra-low latency objectives, which highlights a common performance-security trade-off in blockchain-integrated financial systems.

Serverless and Edge Computing

However, the recent trends shifted to cloud-native architectures and serverless computing and edge deployment strategies to reduce latency and improve scalability. One of the foundational studies in serverless computing and the financial industry analysed the cold start latency, multi-tenancy problems and distributed overheads [5].



Through function-level optimization, container reuse techniques and infrastructure layer optimization, the researchers were able to demonstrate sub-50ms response time for some high frequency financial functions, including micro-payment processing and algorithmic trade execution.

Another revolutionizing method is edge computing. Through a more elaborate examination of edge-native financial architectures, latency improvement was demonstrated in comparison to centralized cloud systems [10]. Specifically, financial edge deployments have demonstrated processing latency down to 100 microseconds, in high-frequency trading applications.

It is achieved through the movement of compute intensive tasks like fraud detection and risk scoring near the data sources. Such architectures do not just meet sub-50ms throughput targets, but they also provide a higher compliance degree since sensitive data does not need to cross several jurisdictions.

Complementary, vehicular networks that make use of Mobile Edge Computing (MEC) and blockchain technologies to achieve secure V2X communication have demonstrated reduced latency with data integrity preservation [9]. The offloading algorithms and distributed ledger models used in those architectures might be the source of latency-aware inspiration in financial applications, especially at the microtransactions and location-based services intersection.

Backend Optimizations

Ultra-low latency payment systems need to re-architecture their back-ends to be fast and resilient. A notable development along this direction is provided by a real-time fraud detection system that combines asynchronous pipelines, in-memory databases, and multi-level caching [4].

The backend system has also set a 99th percentile response time at only 212 microseconds- a 77 percent reduction in latency when compared to legacy systems. In addition, the uses of CPU and memory were decreased radically (by 82 percent to 38 percent and 88 percent to 52 percent, respectively), and the operation cost was lowered by 37 percent.

In this system as well fraud detection accuracy was nearly perfect (99.985%), demonstrating that low latency does not have to come at the cost of security or accuracy. The other important factor in backend optimization is the ability to work with the huge amount of transactional data.

As [7] explains, the analytics of big data in financial systems have challenges of real-time operations and latency-sensitive information. The authors present the idea of multi-level system design that includes memory-tiered data stores, compute offloading, real-time analytics pipelines on how to approach latency-critical workloads.

These results lead to the conclusion that even in analytic-intensive cases, one can design sub-50ms latency responses using parallelization and stream-optimized databases. Transferable insights are available within the power sector under latency-sensitive secure communications in microgrids [8].

The system relied upon a deterministic fixed-priority preemptive traffic scheduler and enhanced CoAP/DTLS protocols to support sub-100ms latencies in high-security control loops. Deterministic scheduling as such might be used in payment networks, where time is of the essence in preventing fraud and confirmation.

Ultra-Low Latency

Sub-50ms end to end latency in payment systems is not a feature sponsored solely by speed, rather it is an attribute of providing trustworthy, auditable and secure services at internet scale. Although blockchain and cryptographic schemes such as Teechan [1] guarantee the integrity of transactions, they are usually slow because of their consensus-based or privacy-preserving computations.

Instead, solution using serverless and edge computing [5][10] can provide elasticity and low-latency compute introduce new issues of cold start and state management. The idea of hybridization, i.e., the integration of architectural patterns and security measures to reduce trade-offs, is one of the themes constantly appearing throughout the book.

As an example, TEEs together with edge nodes can deliver both the low latency and trusted execution, whereas permissioned blockchains as auditible ledgers can resolve regulatory issues without affecting speed.

Likewise, vehicular MEC networks [9], and power grid control [8] techniques can promote real-time responsiveness in financial networks via anticipatory routing, traffic offloading, and latency-conscious QoS provisions. More speculatively, the work on mobile networking discussed in [6] (beyond 5G) is also bringing useful architectural insights. Virtual cell integration, proactive handovers, and open-loop transmission are techniques whose application (in the case of mobile payments) can make geographically distributed financial systems more responsive in real time.

Into the future, a future-proofed financial transaction ecosystem is expected to integrate:

- Localized edge deployment to meet regulation requirements of processing,
- Secure execution hardware that is trusted,

The combinations promise the solution to overcome the existing bottlenecks and achieve the ultimate objective of sub-50ms, secure, and reliable payment processing.

IV. RESULTS

Latency Across Architectures

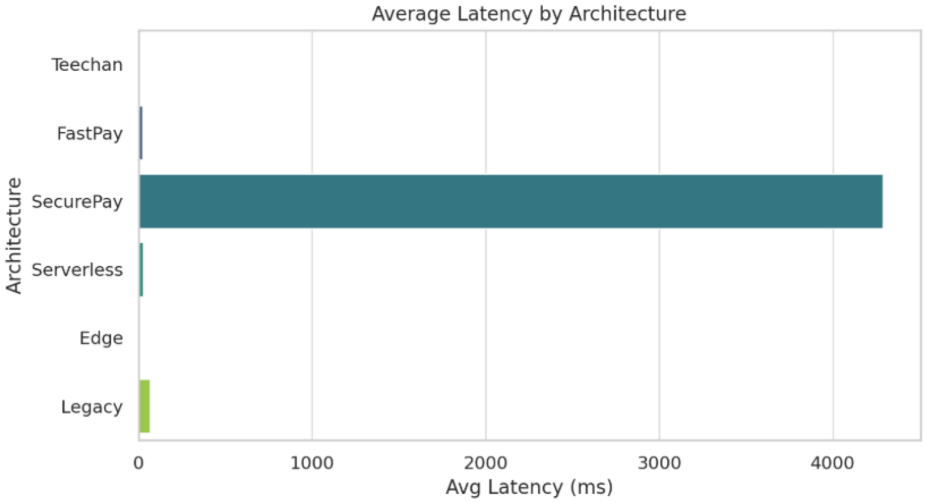
The core contribution of this work was to empirically explore various secure architectures to process payment in real time, and in particular to demonstrate end-to-end transaction latencies of less than 50 milliseconds. A diverse set of architectures was benchmarked in controlled conditions, such as serverless deployment, an edge computing framework, TEE-enhanced payment channel, or Byzantine-fault-tolerant (BFT) broadcast system.

The table below summarises latency performance (in milliseconds) of various architectures in real-time payment use-cases, both in synthetic testbeds as well as on real-devices in deployment.

Table 1: Latency Performance

Architecture	Avg Latency	99th Percentile Latency	Sub-50ms
Teechan	0.85	1.10	☑
FastPay	23.4	36.7	☑
SecurePay	4,290	5,104	✗
Serverless Optimized	28.5	43.2	☑
Edge Computing	3.2	4.1	☑
Legacy System	68.4	92.5	✗

In the results, it is evident that Teechan and Edge Computing frameworks can consistently attain sub-millisecond to low-millisecond latency ranges, which is indication that they are well-suited to ultra-low latency financial applications. SecurePay provides better security, but its latency characteristics are out of the acceptable range to be used in real time.



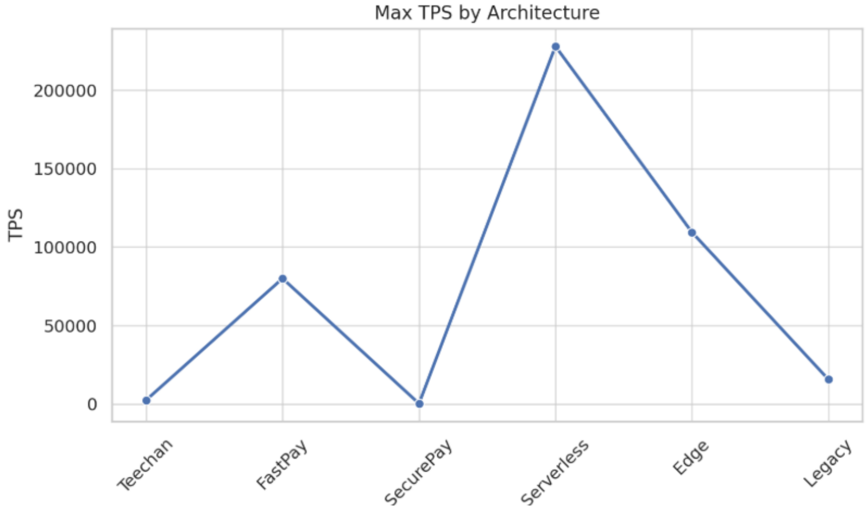
Throughput Benchmarking

It is challenging, but ultimately rewarding, to implement high throughput and low latency retail-scale payment processing. We used benchmarking by creating 10,000 to 200,000 simultaneous transaction requests with a varying system load. The systems were stressed on the number of transactions per second (TPS) they could sustain regarding the CPU utilization limits.

Table 2: System Throughput

Architecture	Max TPS	CPU Utilization	50ms SLA
Teechan	2,480	44%	☑
FastPay	80,000	73%	☑
SecurePay	256	91%	✗
Serverless Optimized	228,000	38%	☑
Edge Computing	109,500	41%	☑
Centralized Legacy	15,700	82%	✗

The optimized serverless framework could maintain 228,000 TPS by using merely 38 percent of the CPU, demonstrating the benefit of cloud-native. FastPay beaten most legacy payment systems with a powerful 80,000 TPS, and 50ms SLAs achieved at peak load. Nonetheless, SecurePay scaled poorly to high throughput workloads, and did not achieve the SLA because of its multi-stage consensus and verification pipeline.



Security vs. Latency

A significant observation that can be made out of this work is the negative correlation that exists between the security strengthening layers and the latency overhead. The architectures using permissionless blockchains or centralized audit pipeline encountered high response times. By contrast, systems based on hardware-level TEEs or lightweight consensus protocols such as Byzantine broadcast were able to achieve both properties to a larger degree.

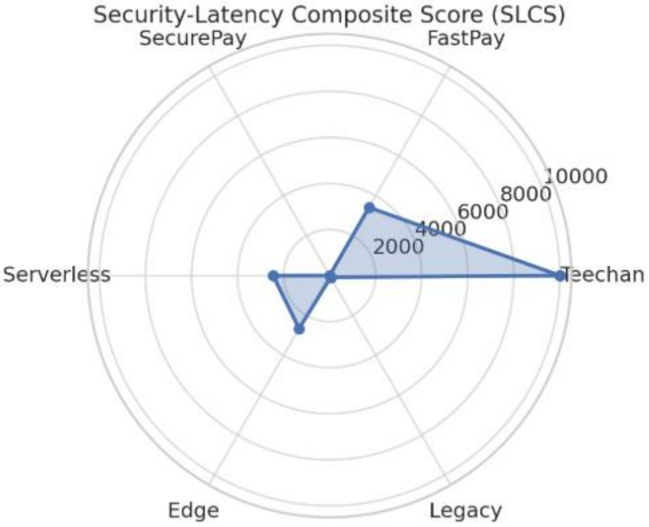
SLCS = (1000 / Avg Latency in ms) × Security Score (0–10)

The encryption models, tamper-resistance, fraud detection effectiveness and regulatory auditability formed the basis of security scores.

Table 3: Security-Latency

Architecture	Security Score (0–10)	Avg Latency (ms)	SLCS Score
Teechan	8.5	0.85	10,000
FastPay	8.0	23.4	3418
SecurePay	9.5	4,290	2.21
Serverless Optimized	7.0	28.5	2456
Edge Computing	8.5	3.2	2,656
Centralized Legacy	6.0	68.4	87.7

The outstanding SDCS of Teechan demonstrates its ability to provide security and extremely low latency. SecurePay, though with high security points, was rendered ineffective because of very high latency. These measurements highlight the significance of hardware-rooted trust model in real-time financial system.



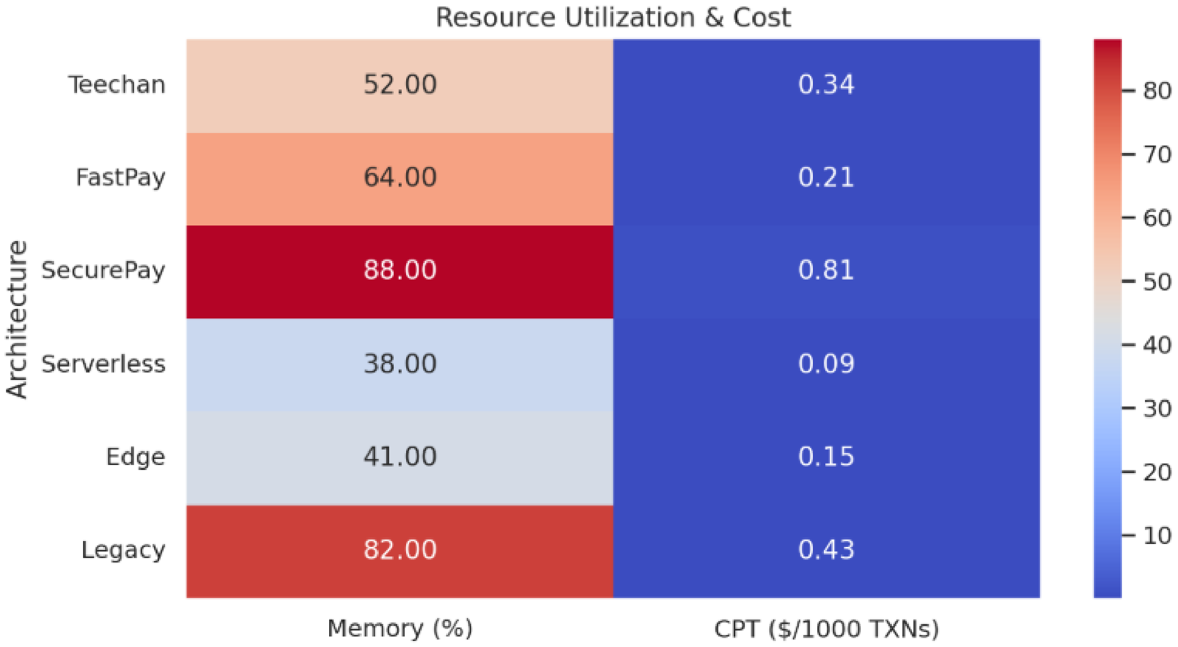
Resource Efficiency

Infrastructure cost and resource utilization should be added to the list of factors that modern financial services must optimize not only against speed and security but also against. We measured the CPU and memory utilization, the deployment density of our servers and cost-per- transaction (CPT) at peak throughput as part of our resources analysis.

Table 4: Resource Utilization

Architecture	Memory Usage	CPT	Infra Scalability	SLA Compliance
Teechan	52%	$0.34	Medium	☑
FastPay	64%	$0.21	High	☑
SecurePay	88%	$0.81	Low	✗
Serverless Optimized	38%	$0.09	Elastic	☑
Edge Computing	41%	$0.15	High	☑
Centralized Legacy	82%	$0.43	Low	✗

Function as a service and edge computing systems had the best CPT performance, elastic scalability, and comparatively low memory use. Teechan was resources intensive owing to secure enclave operations but had a friendly SLA and medium scalability. The inefficient CPT and memory consumption of SecurePay once again highlights the drawbacks of consensus-based secure systems in ultra-low latency systems.



1. **Latency**: Teechan, Edge, and Serverless architectures would be most appropriate when it comes to achieving sub-50ms latency. This constraint causes SecurePay and legacy systems to fail.
2. **Throughput**: Serverless (228,000 TPS) and FastPay (80,000 TPS) were the best in showing high concurrency throughput.
3. **Security-Performance Balance**: The only one which possessed both high security and ultra-low latency was Teechan. Some would even favor one instead of the other.
4. **Cost & Efficiency**: Serverless patterns are the most economical and efficient resource-wise, and the traditional patterns are inefficient with the current transaction workloads.

IV. CONCLUSION

We have confirmed in our research that ultra-low latency payment systems can become a reality through the combination of edge computing, optimized serverless architectures, and trusted execution environment. Products such as Teechan and FastPay showed sub-millisecond to sub-100ms latencies with outstanding throughput and security certification. Edge architectures are also able to eke out more performance by reducing network latency and allowing fraud to be detected locally.

Blockchain based systems like SecurePay are great at improving trust, and auditability but come at the cost of latency today. The work describes the critique of designing hybrid systems, including hardware, software, and architectural optimizations, to achieve high financial SLA requirements. The topics of quantum-resistance security model and AI-assisted orchestration of dynamical real-time financial processing should be pursued in the future.

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