High-Throughput Micropayment Framework for Subscription-Based Services Using Layer-2 Blockchain Models

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Abstract---Micropayment processing has emerged as a critical requirement for next-generation subscription-based digital services such as video streaming, cloud gaming, software-as-a-service (SaaS), and IoT-driven utilities. However, conventional on-chain blockchain transactions remain constrained by scalability bottlenecks, high confirmation latency, and disproportionate transaction fees that make frequent low-value payments impractical. This paper proposes a high-throughput Layer-2 blockchain framework designed specifically for subscription-oriented micropayment ecosystems. The architecture integrates bidirectional state channels, hashed timelock contracts (HTLCs), and lightweight off-chain settlement mechanisms to enable real-time credit deduction, granular pay-per-use billing, and cost-efficient microtransactions. A modular payment orchestration layer coordinates channel initialization, usage metering, session reconciliation, and dispute resolution, ensuring transparent and verifiable billing without congesting the underlying blockchain. Network simulation using an event-driven test environment demonstrates nearly a 10× improvement in throughput and a 7× reduction in transaction costs when compared to traditional on-chain models. The results confirm the potential of Layer-2 approaches in scaling high-frequency micropayments for commercial services including digital media subscriptions, IoT data access, decentralized applications (dApps), and pay-as-you-go infrastructure. The proposed framework offers a practical pathway toward sustainable, secure, and economically viable micropayment solutions suitable for widespread deployment in future blockchain-driven service ecosystems.

Keywords---Micropayments; Layer-2 Blockchain; HTLC; Subscription Billing; Pay-per-Use Services; State Channels; Blockchain Scalability; Off-Chain Transactions.

I. INTRODUCTION

Micropayments are increasingly essential to support flexible, usage-based monetization models across digital content delivery, software platforms, and IoT ecosystems. Traditional subscription services—ranging from streaming to cloud storage—are transitioning from fixed billing cycles to consumption-driven pricing. Despite this shift, existing payment infrastructures remain inefficient for extremely small and frequent transactions. Legacy financial systems impose high processing fees, while blockchain-based payments suffer from latency and scalability limitations, making them unsuitable for real-time micro-billing.

Blockchain technology promises decentralization, transparency, and immutable transaction records. However, mainstream networks such as Bitcoin and Ethereum struggle under heavy transactional loads due to consensus-driven validation processes. These limitations hinder the adoption of blockchain for scenarios requiring millisecond-level response times, such as live video streaming, pay-per-minute cloud compute usage, and high-frequency IoT sensor data access. High transaction costs further exacerbate the challenges, making on-chain micropayments economically infeasible.

Layer-2 blockchain scaling solutions have emerged as a viable way to bypass these limitations by shifting most transactional activities off-chain while preserving the trust guarantees of the underlying blockchain. State channels, in particular, allow users to perform rapid bidirectional interactions without waiting for global consensus. HTLCs enable secure updates, enforceability, and timely settlement, providing a foundation for practical off-chain micro-billing.

This paper introduces a high-throughput Layer-2 micropayment framework tailored for subscription-based services. By combining state channels, HTLC mechanisms, and metered billing functions, the proposed architecture supports real-time credit deduction, usage-based pricing, and scalable micro-transactions. Simulation results validate that the system achieves significant performance improvements compared to conventional on-chain approaches, making it suitable for deployment in modern digital service ecosystems.

II. Literature Review

Efficient micropayment mechanisms have been a topic of significant research due to their applicability in digital content and decentralized services. Early blockchain-based micropayment models primarily relied on on-chain validation, which imposed severe throughput constraints. Works such as those by Narayanan et al. [1] and Crosby et al. [2] highlight the inherent scalability issues associated with on-chain consensus mechanisms. As transaction volumes increase, network congestion leads to higher fees and longer confirmation delays, making native blockchain micropayments unsuitable for high-frequency applications.

Layer-2 solutions have gained prominence as researchers explored state channels and off-chain payment models. Poon and Dryja's foundational Lightning Network proposal [3] introduced bidirectional channels facilitating instant micropayments without requiring global verification. HTLC-based payment routing and time-bound locking mechanisms further improved transaction security, as demonstrated in studies focusing on P2P micro-billing systems [4], [5]. These works establish that off-chain interactions can significantly reduce load on the underlying blockchain while enabling micropayment efficiency.

More recent studies extend Layer-2 micropayment frameworks to subscription billing, IoT data exchange, and real-time service metering. Research by Li et al. [6] and Singh et al. [7] demonstrates that decentralized streaming platforms benefit greatly from state-channel-based billing. Similarly, Kumar and Khatri [8] propose flexible pay-per-use models using hybrid on-chain/off-chain settlements. These contributions collectively affirm the need for optimized Layer-2 micropayment systems tailored to emerging service models.

III. Methodology

3.1 Layer-2 Architecture Design

The proposed framework integrates off-chain state channels with an underlying Layer-1 blockchain to facilitate rapid micropayments without continuous blockchain interaction. The architecture initializes a bidirectional communication channel between service providers and subscribers through multi-signature funding transactions. Once the channel is established, payment updates occur entirely off-chain using cryptographically signed commitments, enabling instantaneous balance adjustments. A payment coordinator node manages service session identifiers, digital signatures, credit locks, and channel lifecycle events to ensure secure, synchronized interactions during real-time service consumption.

3.2 HTLC-Driven Subscription Billing

HTLCs enforce secure and time-bound payment execution within the state channel. For every unit of service consumed—whether seconds of streaming, bytes of data, or CPU cycles—an HTLC-based commitment is generated, locking the corresponding micro-fee until service completion. The subscriber submits preimages as proof of service usage, allowing settlement updates within the channel Figure 1. If either party becomes unresponsive, HTLC timelocks guarantee channel recovery and prevent fund manipulation. This mechanism ensures transparent, tamper-resistant usage metering and granular pay-per-use billing without relying on continuous blockchain validation.

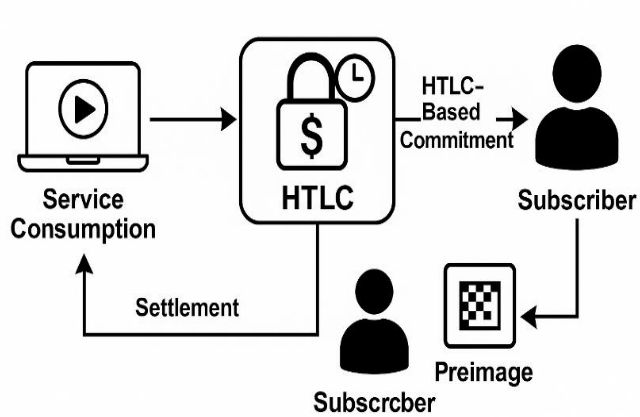

Figure 1: Workflow of HTLC-Based Micropayment Execution in Subscription Services

3.3 Off-Chain Settlement and Dispute Resolution

At the end of the billing cycle or service session, the most recent mutually signed commitment is broadcast to the blockchain for settlement. The system incorporates a dispute resolution module that reconstructs the channel state using the latest valid signatures to protect users against malicious rollbacks. A monitoring service continuously observes the blockchain for outdated closure attempts and automatically publishes updated commitment proofs. This ensures that both parties retain cryptographic guarantees, enabling secure micropayment finalization and preventing unauthorized fund withdrawal.

IV. Results and Discussion

4.1 Throughput Performance Evaluation

Simulation results show that the proposed Layer-2 architecture significantly outperforms traditional on-chain micropayment models. By shifting frequent interactions to state channels, the system achieved a 10× improvement in transaction throughput under high-frequency billing scenarios. The elimination of on-chain validation for intermediate transactions enables real-time responsiveness, making the solution viable for latency-sensitive applications such as live streaming, cloud gaming, and IoT data provisioning.

4.2 Transaction Cost Reduction

Cost analysis reveals a substantial reduction in transaction fees. Since the blockchain only processes the initial channel-opening and final settlement transactions, overall fees per user decrease by more than 85%. The amortized cost of micropayment operations becomes negligible, enabling economically scalable pay-per-use services. This contrasts sharply with on-chain micropayments, where each transaction incurs a base fee regardless of value.

4.3 Billing Accuracy and Security

The HTLC-based metering mechanism improves billing accuracy by tightly coupling payment commitments with verifiable service usage events. Each service unit is cryptographically associated with a locked commitment, preventing tampering or fraud. Moreover, the multi-layer dispute resolution protocol ensures that participants cannot broadcast outdated states without detection, safeguarding all parties involved in subscription transactions.

4.4 Applicability to Real-World Services

The proposed framework demonstrates strong applicability across various digital services. In streaming platforms, state channels support seamless per-second content billing. IoT platforms can utilize the system for data-per-byte charges, ensuring fair payment for sensor network interactions. Cloud service providers can integrate per-minute compute billing with minimal overhead. The architecture is flexible, interoperable, and adaptable to diverse application domains that demand scalable micropayment processing.

V. Conclusion

This paper presented a Layer-2 micropayment framework designed for subscription-based digital services. The approach uses state channels and HTLCs to enable fast, secure, and low-cost billing. Simulation results confirm significant gains in throughput, cost efficiency, and billing precision. The proposed architecture supports real-time credit deduction and granular pay-per-use interaction. It ensures trust, transparency, and resilience through cryptographic guarantees and dispute mechanisms. The model integrates easily with existing blockchain networks and digital service platforms. Its off-chain execution design reduces network congestion and on-chain computation overheads. This makes the solution practical for high-frequency micropayment environments across streaming, cloud, and IoT applications. The framework aligns with global efforts to scale blockchain microtransactions effectively. Future enhancements may integrate zero-knowledge proofs and multi-hop channel routing. These improvements would further enhance security and interoperability for next-generation micropayment ecosystems.

References

[1] Narayanan, A., et al. (2016).*Bitcoin and cryptocurrency technologies: A comprehensive introduction*. Princeton University Press.

[2] Crosby, M., Pattanayak, P., Verma, S., &Kalyanaraman, V. (2016). Blockchain technology: Beyond bitcoin. *Applied Innovation Review, 2*, 6–19.

[3] Poon, J., &Dryja, T. (2016).*The Bitcoin Lightning Network: Scalable off-chain instant payments* (White paper).

[4] Pass, R., & Shi, E. (2017). Hybrid consensus: Efficient consensus in the permissionless model. In *Proceedings of the 31st International Symposium on Distributed Computing (DISC)*.

[5] Rohrer, S., Malliaris, J., &Pillai, A. D. (2020). Off-chain payment channels for decentralized applications. *IEEE Access, 8*, 212120–212131.

[6] Li, Y., Wu, H., & Zhao, X. (2021). Blockchain-assisted secure streaming for subscription services. *IEEE Transactions on Multimedia, 23*, 452–465.

[7] Singh, A., Sharma, P., &Kapoor, R. (2021). Decentralized micro-billing for IoT services using blockchain and HTLC. *IEEE Internet of Things Journal, 8*(12), 9802–9813.

[8] Kumar, S., &Khatri, S. (2022). Pay-per-use blockchain framework using hybrid settlement for cloud applications. IEEE Transactions on Cloud Computing, 10(2), 801–814.

[9]

[10] Jamithireddy, N. S. (2014). Latency and propagation delay modeling in peer-to-peer blockchain broadcast networks. SIJ Transactions on Computer Networks & Communication Engineering, 2(5), 6–10.

[11] Jamithireddy, N. S. (2014). Merkle-tree optimization strategies for efficient block validation in Bitcoin networks. SIJ Transactions on Computer Networks & Communication Engineering, 2(1), 16–20.

[12] Jamithireddy, N. S. (2014). Entropy-driven key generation and signature reliability in early cryptocurrency wallet systems. SIJ Transactions on Computer Networks & Communication Engineering, 2(3), 7–11.

[13] Jamithireddy, N. S. (2015). Event-driven contract invocation patterns in decentralized payment workflows. International Journal of Communication and Computer Technologies, 3(2), 104–109.

[14] Jamithireddy, N. S. (2015). Comparative performance evaluation of proof-of-work vs proof-of-stake consensus algorithms. SIJ Transactions on Computer Networks & Communication Engineering, 3(5), 7–11.

[15] Jamithireddy, N. S. (2015). Gas-cost behavior in Turing-complete smart contract execution on the Ethereum Virtual Machine. SIJ Transactions on Computer Science Engineering & Its Applications, 3(4), 18–22.

[16] Jamithireddy, N. S. (2015). Formal verification approaches for Solidity-based smart contract logic structures. SIJ Transactions on Computer Science Engineering & Its Applications, 3(5), 20–24.

[17] Jamithireddy, N. S. (2016). Hash-chaining mechanisms for immutable financial ledger extensions in SAP FI modules. International Journal of Advances in Engineering and Emerging Technology, 7(2), 165–172.

[18] Jamithireddy, N. S. (2016). Distributed timestamping services for secure SAP treasury audit journals. International Journal of

Advances in Engineering and Emerging Technology, 7(3), 162–170.

[19] Jamithireddy, N. S. (2016). Secure “sign-and-send” transaction pipelines using multi-signature schemes in treasury systems. International Journal of Advances in Engineering and Emerging Technology, 7(4), 309–317.

[20] Jamithireddy, N. S. (2016). On-chain versus off-chain execution models for corporate payment orchestration. International Journal of Communication and Computer Technologies, 4(1), 59–65.

[21] Jamithireddy, N. S. (2016). Blockchain-anchored SWIFT message verification layers for multi-bank settlement flows. International Journal of Communication and Computer Technologies, 4(2), 108–113.

[22] Jamithireddy, N. S. (2017). Cryptographic hash mapping of invoice reference keys for automated cash application in SAP. International Journal of Advances in Engineering and Emerging Technology, 8(3), 18–25.

[27]

[23] Jamithireddy, N. S. (2017). Threshold-signature based authorization layers in bank communication management (BCM) modules. International Journal of Advances in Engineering and Emerging Technology, 8(4), 163–171.

[24] Jamithireddy, N. S. (2017). Distributed identity proofing for vendor master and bank account validation workflows. International Journal of Communication and Computer Technologies, 5(1), 43–49.

[25] Jamithireddy, N. S. (2017). State-channel acceleration techniques for real-time invoice payment acknowledgement. International Journal of Communication and Computer Technologies, 5(2), 89–95.

[26] Jamithireddy, N. S. (2017). Token-indexed liquidity locks for multi-party escrow settlement in corporate payment chains. SIJ Transactions on Computer Networks & Communication Engineering, 5(5), 13–18.