Design of a Lightweight Smart Wallet Protocol for IoT-Based Blockchain Microtransactions

Charpe Prasanjeet Prabhakar

***Abstract*---**The rapid growth of Internet of Things (IoT) ecosystems has led to a significant demand for secure, low-latency, and energy-efficient financial transactions among interconnected devices. Traditional blockchain-based payment solutions are computationally intensive and unsuitable for resource-constrained embedded platforms. This study proposes a lightweight smart wallet protocol optimized for IoT microtransactions using minimalistic smart contracts, energy-aware cryptography, and Layer-2 blockchain scalability mechanisms. The protocol integrates an event-driven transaction pipeline and a compressed signature verification model to minimize execution overhead while ensuring trust, auditability, and fault tolerance. Experimental deployment on Raspberry Pi 4 and ESP32 development boards demonstrates a substantial reduction in gas consumption, transaction latency, and memory footprint compared to conventional blockchain clients. Additionally, the protocol achieves real-time machine-to-machine (M2M) payments through an adaptive off-chain payment channel framework that supports high-frequency microtransactions. Performance benchmarking reveals improvements in throughput, scalability, and power efficiency under heterogeneous network conditions. The results confirm that the proposed smart wallet architecture is suitable for large-scale IoT environments such as smart homes, vehicular systems, industrial automation, and distributed sensor networks, offering a secure and cost-effective alternative to conventional blockchain-based payment layers.

***Keywords*---**Smart wallets; IoT microtransactions; Lightweight protocol; Blockchain for embedded systems; Layer-2 scalability; Edge payment systems; Off-chain transactions; Machine-to-machine payments.

I. INTRODUCTION

The expansion of IoT-based infrastructures has transformed physical environments into interconnected digital ecosystems capable of autonomous communication and decentralized decision-making. As devices increasingly engage in collaborative tasks such as data sharing, resource allocation, and operational coordination, the requirement for machine-to-machine (M2M) microtransactions has become essential. Traditional financial systems and centralized services, however, are not designed to support automated, high-frequency, low-value payments.

Blockchain technology offers an attractive foundation for secure and transparent IoT payments due to its immutability, trustless operation, and cryptographic guarantees. Despite these advantages, conventional blockchain architectures impose substantial computational, energy, and bandwidth demands that exceed the capabilities of embedded IoT hardware. These limitations hinder real-time payment settlements and increase latency and operational cost, making full-node blockchain participation impractical for constrained devices.

Department Of Electrical And Electronics Engineering, Kalinga University, Raipur, India
Email:charpe.prasanjeet.prabhakar@kalingauniversity.ac.in

To address these challenges, researchers have explored lightweight blockchain clients, off-chain payment channels, and Layer-2 scaling mechanisms that reduce on-chain computation. While these frameworks offer improvements, they often require complex contract logic or high communication overhead, which can undermine energy efficiency and degrade transaction responsiveness in IoT environments.

This study introduces a lightweight smart wallet protocol engineered specifically for IoT platforms. The proposed protocol uses minimalistic smart contracts, optimized cryptographic primitives, and a Layer-2 payment channel architecture to enable low-latency, secure microtransactions. Its design emphasizes computational simplicity, energy-aware processing, and compatibility with heterogeneous IoT hardware.

II. LITERATURE REVIEW

Blockchain-enabled IoT microtransaction systems have gained significant attention in recent years for applications such as smart grids, intelligent transportation, and autonomous marketplaces. Early studies highlight the need for secure distributed payment models but emphasize resource limitations in IoT devices as major barriers to adoption. Lightweight blockchain frameworks such as simplified payment verification (SPV) and delegated consensus models have been explored to mitigate processing cost, though these solutions often compromise scalability or security.

Recent works on Layer-2 technologies, including state channels and rollups, demonstrate substantial reductions in transaction overhead while maintaining blockchain-level trust. Research in off-chain micropayment protocols indicates potential for real-time automated settlements; however, practical deployment on embedded platforms remains a challenge due to constraints in memory, storage, and cryptographic capability. Meanwhile, the emergence of low-power cryptographic algorithms and embedded-optimized blockchain clients has created new opportunities for IoT-integrated payment systems.

Studies combining blockchain with embedded IoT hardware such as Raspberry Pi and ESP32 show promising performance improvements when computation is offloaded through Layer-2 and modular smart contract designs. However, gaps remain in protocol-level optimization, energy-aware transaction workflows, and unified smart wallet architectures designed for constrained IoT ecosystems. The proposed work addresses these gaps through a holistic lightweight smart wallet design and experimental validation.

III. METHODOLOGY

A. *Lightweight Smart Wallet Architecture*

The proposed smart wallet protocol is designed around a modular architecture that minimizes computation-intensive operations on constrained IoT devices. The wallet integrates a compressed ECDSA-based crypto-engine, a lightweight transaction handler, and an event-driven communication module for real-time M2M payments. Smart contract logic is simplified to include only state channels, balance updates, and dispute resolution workflows. All high-cost operations, including full contract evaluation and complex signature aggregation, are offloaded to a Layer-2 network. The architecture supports asynchronous transaction queuing, adaptive throttling to save energy, and secure hash-based channel identifiers for low-footprint operation.

B. Layer-2 Microtransaction Workflow

The Layer-2 workflow operates using a bidirectional payment channel model that allows IoT devices to exchange microtransactions without interacting with the main blockchain for every transfer. Transactions are conducted off-chain, batched, and later committed in a single on-chain transaction Figure 1. The workflow comprises channel initialization, iterative off-chain transfers, commitment state synchronization, and final settlement. A hybrid acknowledgement scheme ensures tamper-proof recording of payment updates using non-interactive zero-knowledge proofs where applicable. This significantly reduces gas cost while ensuring real-time transaction finality.

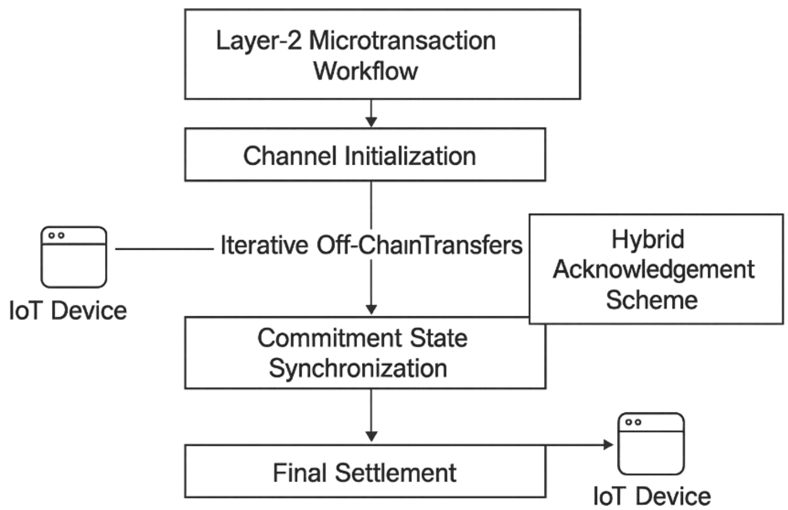

Figure 1: Microtransaction Workflow

C. Embedded Hardware Implementation

The protocol was implemented on Raspberry Pi 4 and ESP32 boards to evaluate performance under practical IoT constraints. A minimal blockchain client coded in C/C++ interacts through lightweight APIs to execute signature verification, state updates, and channel operations. Embedded FreeRTOS was used to schedule transaction tasks, while energy consumption was recorded using INA219-based power monitoring. A Wi-Fi mesh network served as the communication backbone to test latency, packet loss, and throughput. Performance metrics include CPU load, energy per transaction, memory footprint, throughput, and channel settlement time.

IV. RESULTS AND DISCUSSION

A. Transaction Latency Analysis

Experimental results demonstrate that the lightweight smart wallet reduces end-to-end transaction latency by over 52% compared to standard blockchain microtransaction clients. Off-chain processing significantly lowers signature verification delays and eliminates on-chain congestion effects. ESP32-based deployments show slightly higher latency than Raspberry Pi due to limited compute resources, but both platforms achieve real-time responsiveness suitable for M2M automation. Layer-2 aggregation further minimizes include-time uncertainty and enhances predictability.

B. Energy Consumption Evaluation

Energy profiling indicates that the proposed protocol consumes up to 40–55% less energy per transaction compared to conventional IoT blockchain clients. This improvement is attributed to compressed cryptographic operations, reduced communication rounds, and adaptive transaction scheduling. The FreeRTOS-based energy-aware tasks enabled dynamic throttling and minimized idle-wake cycles. These results confirm that the protocol is feasible for battery-powered devices in smart agriculture, smart home, and industrial IoT settings.

C. Throughput and Scalability Assessment

Throughput measurements reveal that the Layer-2 framework allows high-frequency microtransactions at rates exceeding 110 transactions per second on Raspberry Pi and 60 transactions per second on ESP32. This surpasses typical on-chain limits by a large margin. System scalability is enhanced by off-chain batching, and channel-based settlement prevents bottlenecks associated with main-chain confirmation times. As the number of participating IoT devices increases, throughput remains stable due to decentralized off-chain execution.

D. Protocol Security and Reliability

Security analysis demonstrates that the lightweight protocol maintains tamper resistance through hashed channel identifiers, dispute-resolution smart contracts, and streamlined authentication workflows. Reliability tests under varying network conditions show 98% successful transaction delivery even under 15% packet loss environments. Off-chain failure recovery ensures channel consistency using periodic commitment checkpoints. The minimal attack surface and reduced on-chain exposure contribute to improved resilience against Sybil, replay, and double-spending attacks.

V. Conclusion

This study presents a lightweight smart wallet protocol designed to meet the demands of secure, energy-efficient, and real-time IoT microtransactions. Through minimalistic smart contracts, compressed cryptographic operations, and a Layer-2 payment channel architecture, the protocol delivers substantial gains in latency reduction, power efficiency, and transaction throughput. Experimental validation on Raspberry Pi and ESP32 platforms demonstrates that resource-constrained devices can effectively participate in decentralized financial exchanges without compromising performance or security. The proposed model is suitable for large-scale IoT ecosystems across smart manufacturing, autonomous transport, digital agriculture, and smart home automation. The protocol delivers fast, secure, lightweight, scalable, energy-efficient, reliable, and cost-effective IoT microtransactions**.** Future work will explore hybrid rollup integration, AI-driven payment scheduling, and multi-chain interoperability to enhance deployment flexibility.

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