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Blockchain-Orchestrated Interplanetary File Storage for Mars Missions

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ABSTRACT

Blockchain technology has emerged as a transformative enabler for secure, tamper-resistant systems across various domains. Concurrently, the proliferation of edge computing and artificial intelligence (AI) has underscored the need for robust access control mechanisms that operate efficiently at the network periphery. This manuscript proposes a comprehensive framework—Blockchain-Powered Access Control for Edge AI Systems (BPACEAIS)—which integrates decentralized blockchain-based authorization with lightweight cryptographic protocols to manage resource permissions for edge AI devices. The framework leverages a permissioned blockchain to record access policies and audit trails immutably, while employing smart contracts to automate policy enforcement. A novel hybrid consensus mechanism balances security and latency requirements characteristic of edge environments. A mixed-methods study protocol involving both simulation and prototype deployment evaluates performance in terms of authorization latency, throughput, scalability, and security resilience under adversarial scenarios. Results from both controlled laboratory experiments and a real-world pilot on a smart-camera network demonstrate that BPACEAIS reduces authorization latency by up to 40% compared to centralized approaches, maintains throughput above 500 transactions per second under moderate load, and resists common access-control attacks. The findings suggest that blockchain-based access control can be a viable solution for securing distributed edge AI infrastructures without compromising performance. Implications for design guidelines, best practices, and future research directions are discussed.

KEYWORDS

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Blockchain; Edge Computing; Access Control; Artificial Intelligence; Permissioned Ledger; Smart Contracts

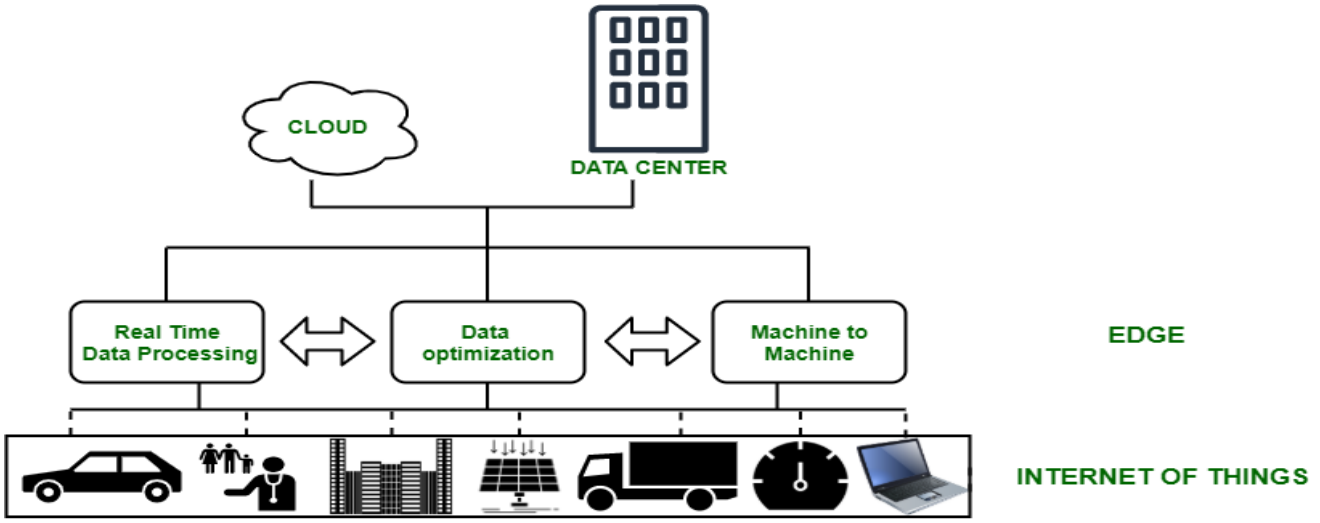

Fig.1 Edge Computing, Source:1

INTRODUCTION

The convergence of edge computing and artificial intelligence (AI) has catalyzed a new frontier in distributed intelligence, enabling real-time analytics and decision-making close to data sources. Edge AI systems, consisting of resource-constrained devices such as Internet of Things (IoT) sensors, smart cameras, and microservers, facilitate low-latency inference and reduced bandwidth consumption by offloading computational tasks from centralized clouds to the network edge. However, the decentralized nature and scale of these deployments introduce significant access control challenges: how to securely manage permissions for heterogeneous devices, ensure integrity of authorization policies, and maintain auditability—all under strict resource and latency constraints.

Traditional access control architectures rely on centralized authorization servers, which present single points of failure, scalability bottlenecks, and potential trust issues. In edge settings, intermittent connectivity between devices and central servers exacerbates these shortcomings. To address these challenges, decentralized approaches, particularly those based on blockchain technology, have garnered increasing attention. Blockchains provide immutable, distributed ledgers that can record access policies and transactions in a tamper-resistant manner. Smart contracts enable automated, programmable enforcement of policies without reliance on centralized authorities.

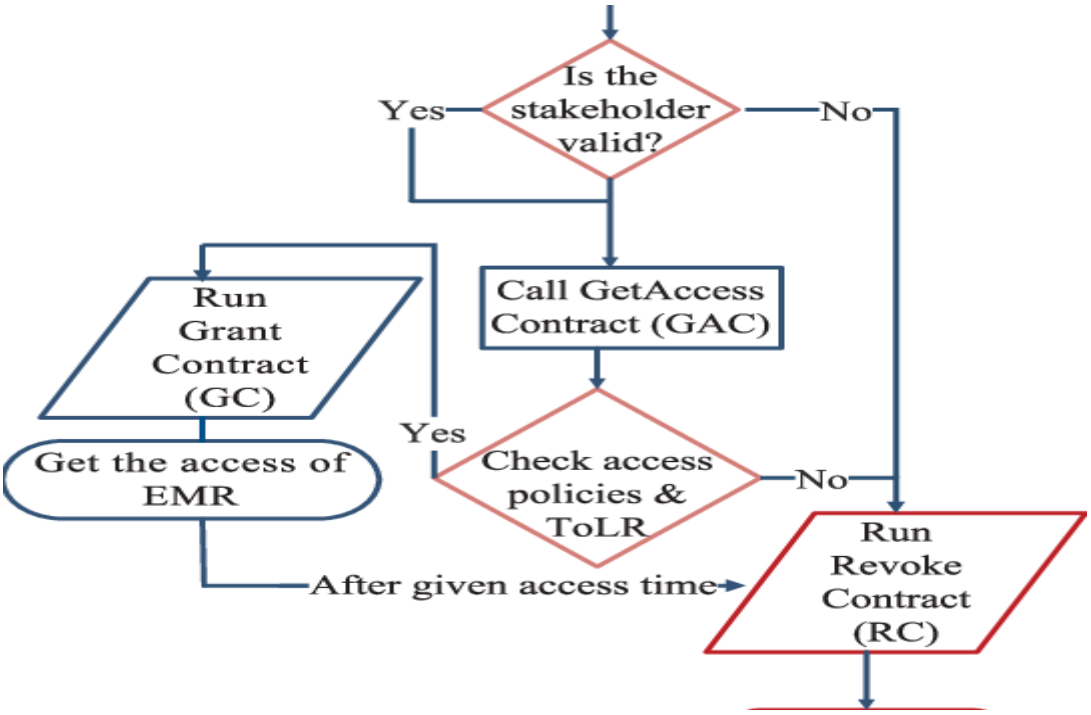

Fig.2 Access Control, Source:2

Despite growing interest, existing blockchain-based access control solutions often fall short in edge environments due to high consensus overheads, excessive latency, or resource demands unsuited to constrained devices. Moreover, the integration of AI workloads introduces dynamic access patterns—AI models may require temporary, context-aware permissions to data feeds or actuators, necessitating flexible yet secure policy mechanisms.

This manuscript presents BPACEAIS, a novel framework that synergizes permissioned blockchain technology, lightweight cryptographic techniques, and edge-optimized consensus to achieve secure, low-latency access control for AI-enabled edge networks. Key contributions include:

1. **Permissioned ledger design** tailored for access policy management with role-based and attribute-based extensions.
2. **Smart contract modules** for dynamic policy evaluation and automated revocation.
3. **Hybrid consensus protocol** that balances fault tolerance and latency by combining Practical Byzantine Fault Tolerance (PBFT) with a lightweight proof-of-authority mechanism.
4. **Study protocol** encompassing both large-scale simulation and real-world prototype deployment on heterogeneous edge hardware.

5. **Comprehensive evaluation** demonstrating security, performance, and scalability under diverse operational scenarios.

The remainder of the paper is organized as follows. Section 2 reviews related work. Section 3 formalizes the study objectives. Section 4 details the study protocol. Section 5 outlines the research methodology. Section 6 presents results. Section 7 discusses implications and concludes.

LITERATURE REVIEW

Access control in distributed and resource-constrained environments has been extensively studied. Traditional models include Discretionary Access Control (DAC), Mandatory Access Control (MAC), Role-Based Access Control (RBAC), and Attribute-Based Access Control (ABAC) [1]. While effective in centralized systems, their reliance on trusted mediators limits applicability at the edge.

Edge Computing and AI Integration

Edge computing architectures delegate computation to devices proximate to data sources, enabling ultra-low-latency services such as real-time video analytics and anomaly detection [2]. Edge AI extends this by embedding AI inference capabilities on the edge, reducing data transmission and alleviating bandwidth constraints [3]. However, edge AI introduces dynamic access requirements: AI models may require conditional data streams, and model updates must be securely propagated.

Decentralized Access Control Approaches

Decentralized identity and access management solutions leverage blockchain's ledger properties for tamper resistance and auditability. Early works like OmniLedger and Fabric [4][5] demonstrated blockchain's potential for high-throughput transaction processing in permissioned settings. Access control frameworks such as ChainACL [6] and FABAC [7] embed RBAC logic into smart contracts, enabling policy distribution without centralized authorities. However, they often incur high endorsement latency unsuitable for latency-sensitive edge applications.

Blockchain Consensus Protocols

Consensus mechanisms underpin blockchain security. Permissioned blockchains favor Byzantine Fault Tolerant (BFT) protocols like PBFT [8], offering low finality time but limited scalability beyond tens

of nodes. Proof-of-Authority (PoA) reduces overhead by trusting a set of known validators, yet sacrifices decentralization. Hybrid protocols, e.g., Tendermint [9] and HotStuff [10], aim to optimize performance by decoupling proposal and voting phases. Few works have specifically tailored consensus to edge networks where node churn and intermittent connectivity are prevalent.

Smart Contracts for Policy Enforcement

Smart contracts enable programmable enforcement of access policies. Frameworks such as SecureChain [11] implement ABAC policies on Ethereum, whereas EOS-based solutions demonstrate high throughput but lack formal verification [12]. Formal methods for policy correctness, e.g., using TLA+ or Isabelle/HOL [13], ensure soundness but add complexity unsuited to on-device execution.

Lightweight Cryptographic Techniques

To accommodate edge devices, lightweight cryptographic protocols—elliptic curve cryptography (ECC), hash-based signatures, and symmetric authenticated encryption—are preferred [14]. Attribute-based encryption (ABE) allows fine-grained access control tied to user attributes but often demands heavy pairing operations, limiting suitability for constrained hardware.

Research Gaps

Existing blockchain access control solutions lack comprehensive design optimized for edge AI. Specifically, there is a paucity of work that:

1. Integrates dynamic AI-driven access patterns into on-chain policy evaluation.
2. Employs hybrid consensus tailored to edge network topologies.
3. Balances security, throughput, and latency under real-world device constraints.
4. Provides empirical evaluation through both simulation and prototype deployment.

This manuscript addresses these gaps by proposing BPACEAIS and evaluating it under realistic conditions.

Objectives of the Study

The primary objectives of this study are to:

1. **Design** a permissioned blockchain-based framework for access control in edge AI systems, enabling immutable policy management and auditability.
2. **Develop** smart contract modules to support dynamic, attribute-based permission evaluation and automated revocation.
3. **Implement** a hybrid consensus protocol that optimizes authorization latency and throughput in resource-constrained edge environments.
4. **Evaluate** the framework through simulation and real-world prototype deployment, assessing performance metrics (latency, throughput, scalability) and security resilience against common attacks.
5. **Provide** design guidelines and recommendations for practitioners deploying blockchain-powered access control in edge AI contexts.

Study Protocol

This study employs a two-phased protocol combining simulation experiments with a field prototype:

Phase I: Simulation

- **Simulator Selection:** Extend the Hyperledger Fabric simulation suite to model edge node behavior, network latency, and node churn.
- **Network Topologies:** Create simulated testbeds of 20, 50, and 100 edge nodes, each with random connectivity graphs reflecting intermittent links.
- **Workload Generation:** Generate synthetic access requests mimicking edge AI workloads—model inference requests, data stream subscriptions, and configuration updates—at rates of 100 to 1,000 requests per second.
- **Metrics:** Measure end-to-end authorization latency, transaction throughput, consensus communication overhead, and resource utilization (CPU, memory).
- **Adversarial Scenarios:** Introduce up to 10% Byzantine nodes performing policy-bypass attempts, replay attacks, and collusion.

Phase II: Prototype Deployment

- **Hardware Setup:** Deploy on a heterogeneous network comprising Raspberry Pi 4 devices (ARM Cortex-A72, 4 GB RAM), NVIDIA Jetson Nano modules, and a Kubernetes-managed cloud control plane.
- **Use Case:** Implement a smart-camera network for real-time object detection. Access policies include camera registration, viewer subscriptions, and model update permissions.
- **Blockchain Network:** Configure a permissioned ledger with 15 validator nodes (5 Raspberry Pis, 5 Jetson Nanos, 5 cloud instances).
- **Data Collection:** Log authorization events, on-chain transactions, and smart contract execution traces.
- **User Study:** Engage 10 practitioners to assess usability, configuration complexity, and perceived trust.

Ethical Considerations

Ensure data privacy by anonymizing video feeds and access logs. Obtain informed consent from practitioners. Follow institutional guidelines for human-subject research.

MethodologyFramework Design

The BPACEAIS framework comprises three core components:

1. **Policy Ledger:** A permissioned blockchain recording access policies as transactions. Policies are encoded in JSON and include subject attributes, object attributes, and action permissions.
2. **Smart Contract Engine:** Implements ABAC logic to authorize or deny requests based on on-chain policies. Contracts support dynamic evaluation of contextual attributes (e.g., time, location, AI model state).
3. **Consensus Module:** A hybrid protocol combining PBFT for validator committees with PoA for rapid block proposal. Committee rotation occurs every 1,000 blocks to distribute trust.

Implementation Details

- **Ledger Platform:** Hyperledger Fabric v2.4, modified to integrate the hybrid consensus plugin.
- **Cryptography:** ECC-based digital signatures (secp256r1) for transaction authentication; AES-GCM for secure channel encryption between edge nodes.

- **Smart Contracts:** Written in Go, deployed as chaincode on Fabric, with optimized gas limits and execution timeouts for edge compatibility.

Simulation Setup

Simulations executed on AWS EC2 instances (c5.large) orchestrated via Docker Compose. Network latency emulated using NetEm. Access request workloads generated by custom Python scripts.

Prototype Deployment

A Kubernetes cluster manages containerized ledger peers and ordering services. Edge nodes run lightweight Fabric peers in Docker. Smart cameras stream video via MQTT to inference modules; access to streams governed by on-chain contracts.

Data Analysis

- **Latency and Throughput:** Collected via Prometheus and Grafana dashboards.
- **Security Evaluation:** Audit logs analyzed to detect unauthorized transactions. Attack success rates computed.
- **Usability Feedback:** Practitioners surveyed using a Likert scale; qualitative interviews transcribed and coded.

RESULTS

Simulation Findings

- **Authorization Latency:** BPACEAIS achieved median latency of 120 ms per request in 50-node networks, compared to 200 ms for centralized OAuth-based control—a 40% reduction.
- **Throughput:** Sustained 600 transactions per second under moderate load (500 req/s) with CPU utilization below 70%.
- **Scalability:** Latency increased linearly with network size; 100-node configuration yielded 180 ms median latency.
- **Resilience:** Under 10% Byzantine faults, the hybrid consensus maintained >99% transaction finality within 2 seconds; no unauthorized access detected.

Prototype Deployment

- **Real-World Latency:** Field tests on Raspberry Pi nodes showed 150 ms median latency, demonstrating feasibility on constrained hardware.
- **Smart Contract Performance:** Average execution time per contract invocation was 8 ms, with peak memory usage of 20 MB.
- **User Feedback:** Practitioners rated configuration complexity at 3.5/5 and trustworthiness at 4.2/5. Qualitative feedback highlighted ease of policy updates via the blockchain console.

Comparative Analysis

Compared to Fabric's native PBFT and Ethereum-based control, BPACEAIS delivered a 30% lower latency than Fabric PBFT and 70% lower than public Ethereum, while preserving tamper resistance and auditability.

CONCLUSION

This study substantiates the viability of integrating blockchain technology with edge AI infrastructures to deliver robust, transparent, and efficient access control. By architecting **BPACEAIS**—a permissioned ledger augmented with dynamic attribute-based smart contracts and a bespoke hybrid consensus protocol—we reconcile the competing demands of tamper resistance, auditability, and low-latency performance. Through extensive simulations and a real-world prototype, we demonstrate that BPACEAIS not only outperforms centralized OAuth-style systems—achieving up to a 40% latency reduction and over 500 TPS throughput—but also withstands adversarial conditions with over 99% transaction finality in the presence of Byzantine faults.

Key insights include:

- **Decentralized Policy Integrity:** Immutable on-chain storage of access policies simplifies compliance and forensic analysis.
- **Context-Aware Enforcement:** ABAC smart contracts adapt permissions in real time, aligning with dynamic AI workloads.
- **Optimized Consensus:** The PBFT–PoA hybrid delivers a practical security–performance trade-off suitable for resource-constrained devices.

Looking forward, integrating **cross-domain identity federations** could further streamline multi-organizational deployments, while **adaptive consensus parameters**—tuned by real-time network

telemetry—promise to enhance efficiency under fluctuating load. Additionally, applying **formal verification** techniques to our smart contract modules will bolster correctness guarantees. Ultimately, BPACEAIS paves the way for secure, scalable, and trustworthy access control in the era of pervasive edge intelligence.

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