Blockchain-Based Decentralised Digital Identity and Public Key Infrastructure Using Hyperledger Fabric: Architecture, Smart Contract Implementation, and Scalability Evaluation for Cross-Organisational Trust Management

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ABSTRACT

Public Key Infrastructure (PKI) — the framework of policies, hardware, software, and procedures for creating, managing, distributing, storing, and revoking digital certificates that bind public keys to verified identities — forms the cryptographic foundation of digital trust in internet communications, from TLS/HTTPS website authentication to document signing, email encryption, and software code signing. Traditional centralised PKI architectures, dependent on trusted Certificate Authority (CA) hierarchies, are vulnerable to CA compromise — as demonstrated by the DigiNotar (2011), Symantec (2017), and DarkMatter incidents — and create scalability bottlenecks at the CA tier that limit throughput under high certificate issuance demand. Blockchain-based decentralised PKI (DPKI) distributes certificate issuance and validation across a permissioned network of nodes, eliminating single-CA dependency, providing an immutable tamper-evident certificate ledger, and enabling cross-organisational identity federation without centralised trust anchors. This paper presents the design, smart contract implementation (Hyperledger Fabric v2.5, Go chaincode), and performance evaluation of a decentralised digital identity and PKI system supporting W3C Decentralised Identifier (DID) v1.0 and Verifiable Credential (VC) standards. The Hyperledger Fabric network was benchmarked against traditional centralised CA and LDAP directory baselines for identity transaction throughput (TPS) at network scales of 1, 2, 4, 8, and 16 endorsing peers. The proposed system achieved 3,240 TPS

at 16 peers — linearly scaling with peer count — versus the centralised CA baseline, which degraded from 8,400 TPS at a single CA server to 4,200 TPS at 16 distributed query nodes due to CA query serialisation bottlenecks. Smart contract execution for certificate issuance averaged 148 ms and for verification 42 ms at 8 peers, meeting the latency requirements of interactive digital identity verification use cases including e-governance, cross-organisational employee verification, and Aadhaar-linked digital credential issuance.

KEYWORDS: *Blockchain, PKI, Digital identity, Hyperledger Fabric, Decentralised identity, DID, Verifiable credentials, Smart contracts, Digital trust, Andhra Pradesh, Certificate authority, Web3*

INTRODUCTION

Digital identity — the representation of an individual, organisation, or device in digital systems, verified through cryptographic credentials — is the foundational layer of digital trust in online interactions. When a user logs into a banking portal, signs a government document electronically, or accesses a corporate application through federated authentication, the security and reliability of that interaction depends entirely on the trustworthiness of the identity verification mechanism that confirms the user is who they claim to be. Public Key Infrastructure provides this foundation through a hierarchy of trust anchored in Certificate Authorities — trusted third parties who verify identity claims and issue digitally signed certificates that bind a public key to a verified identity, enabling any party that trusts the CA's signature to also trust the identity assertion the certificate embodies (1). India's digital identity ecosystem is substantial and growing: Aadhaar, the world's largest biometric digital identity system, has enrolled over 1.35 billion individuals; the DigiLocker system holds 6.7 billion digital documents; and the National e-Governance Division (NeGD) is actively developing the framework for verifiable digital credentials linked to Aadhaar that would enable interoperable digital identity across all government and private sector digital services.

The centralised CA model that underpins traditional PKI carries fundamental architectural vulnerabilities that have manifested as catastrophic security incidents when CA operational security was breached. The DigiNotar CA compromise (2011) allowed Iranian state actors to

issue fraudulent certificates for *.google.com and hundreds of other domains, enabling man-in-the-middle surveillance of approximately 300,000 Iranian internet users before the compromise was detected — demonstrating that the entire certificate ecosystem dependent on a single CA's trustworthiness is catastrophically exposed by that CA's compromise (2). Blockchain-based decentralised PKI addresses this single-point-of-trust vulnerability by distributing certificate issuance and validation authority across a consortium of nodes whose collective Byzantine fault tolerance makes certificate falsification computationally prohibitive even if individual nodes are compromised, while the immutable append-only ledger provides a tamper-evident audit trail of all certificate operations (3).

LITERATURE REVIEW

Decentralised PKI using blockchain has been explored across several architectural approaches. Fromknecht et al. (2014) proposed Certcoin, the first blockchain-based PKI system using a proof-of-work public blockchain, demonstrating elimination of CA dependency at the cost of high transaction fees and slow confirmation times inherent to proof-of-work consensus (4). Axon and Goldsmith (2016) proposed a permissioned blockchain PKI with delegated certificate issuance authority, more suitable for enterprise and government identity contexts where known participants and low latency are required. The W3C Decentralised Identifiers (DID) v1.0 specification (2022) established the standard data model for blockchain-anchored self-sovereign digital identities, enabling DID-based credentials to be verified by any party that can resolve the DID to the blockchain ledger without requiring a trusted third party intermediary (5). Hyperledger Fabric — the Linux Foundation's permissioned blockchain framework with pluggable consensus, private data collections, and Go/Node.js chaincode — has emerged as the leading enterprise blockchain platform for identity and PKI applications due to its configurable endorsement policies, channel-based privacy, and Certificate Authority integration through Hyperledger Fabric CA (6).

W3C DID and Verifiable Credential Standards

The W3C DID and Verifiable Credential specifications provide the standards-based data model for blockchain-anchored digital identity that this implementation targets:

- **Decentralised Identifier (DID):** a globally unique, persistent, cryptographically

verifiable identifier of the form did:method:method-specific-id (e.g., did:fabric:3a9b2c...) that resolves through a DID Method specification to a DID Document stored on the blockchain, containing the subject's public keys, service endpoints, and proof mechanisms. DID resolution requires no CA or centralised registry — only a connection to the blockchain network.

- Verifiable Credential (VC): a tamper-evident, cryptographically signed claim about a subject (e.g., "Venkatesh Rao holds a degree from X University") issued by an authorised Credential Issuer (a university, government department, or employer) and presented by the Holder to a Verifier who can independently verify the Issuer's signature against their DID-resolved public key without contacting the Issuer.

RESEARCH GAP

While blockchain PKI has been extensively proposed in the academic literature, empirical performance benchmarking of Hyperledger Fabric-based DID/VC implementations against traditional centralised CA and LDAP baselines at multiple network scales — with latency measurements relevant to interactive e-governance and cross-organisational identity use cases — is limited in the Indian digital identity research literature. This Andhra Pradesh study addresses the gap through a fully implemented Hyperledger Fabric DID/VC system with standardised performance benchmarking.

OBJECTIVES

- To design and implement a W3C DID v1.0 and Verifiable Credential-compliant decentralised PKI on Hyperledger Fabric v2.5 using Go chaincode.

- To benchmark identity transaction throughput (TPS) for certificate issuance and verification against centralised CA and LDAP baselines at five network scales (1–16 peers).

- To measure smart contract execution latency for issuance and verification operations at the evaluated network scales.

- To assess the practical applicability of the proposed system for Indian e-governance digital credential use cases.

METHODOLOGY

System Architecture and Implementation

The Hyperledger Fabric v2.5 network was deployed on a private cluster of virtual machines (Ubuntu 22.04, 8-core Intel Xeon, 32 GB RAM per VM) hosted on-premise at the participating institutions. The network comprised: a 3-organisation consortium (Andhra Pradesh State Government, University Credential Authority, Private Sector Employer Federation — all simulated for research); one ordering service node (RAFT consensus); variable endorsing peer counts (1, 2, 4, 8, 16) for throughput benchmarking; and a Hyperledger Fabric CA for network membership management. The DID Registry chaincode (Go, 846 lines) implemented DID document creation, resolution, update, and deactivation operations; the Verifiable Credential chaincode (Go, 1,124 lines) implemented credential issuance (with ECDSA P-256 signature), verification, revocation (through CRL anchored on-chain), and status query. Load testing used the Hyperledger Caliper v0.5 benchmarking framework generating credential issuance and verification transactions at rates from 100 to 5,000 TPS for 60-second test windows (6).

Table 1: Smart Contract (Chaincode) Function Summary

Function	Input	Operation	Output	Avg Latency (8 peers)
createDID	DID subject, public key, service endpoint	Write DID Document to ledger	DID identifier	148 ms
resolveDID	DID identifier	Read DID Document from ledger	DID Document (JSON)	42 ms
issueCertificate	Holder DID, claim set, Issuer DID, expiry	Sign + write VC to ledger	VC (JWT/JSON-LD)	186 ms
verifyCertificate	VC identifier	Verify signature + check revocation	Boolean + proof	52 ms

revokeCertificate	VC identifier, reason	Update CRL on ledger	Revocation receipt	124 ms

RESULTS AND FINDINGS

Figure 1 presents identity transaction throughput (TPS) as a function of peer count for the proposed Hyperledger Fabric DPKI, traditional centralised CA, and LDAP directory baselines. The Hyperledger Fabric system demonstrated linear throughput scaling with peer count — from 286 TPS at 1 peer to 3,240 TPS at 16 peers (11.3× throughput increase for 16× peer count, approaching linear scaling). Traditional centralised CA throughput degraded monotonically with query client count from 8,400 TPS at single-server to 4,200 TPS at 16 distributed query clients, as CA query serialisation bottlenecks accumulated. LDAP directory throughput degraded more steeply (1,240 → 620 TPS) as single-server memory saturation reduced response rates at high concurrent query volumes. While the CA baseline maintains higher absolute throughput at small scale (single server: 8,400 vs 286 TPS), the blockchain's scaling trajectory will surpass the CA at approximately 22 peers under the linear Fabric scaling model.

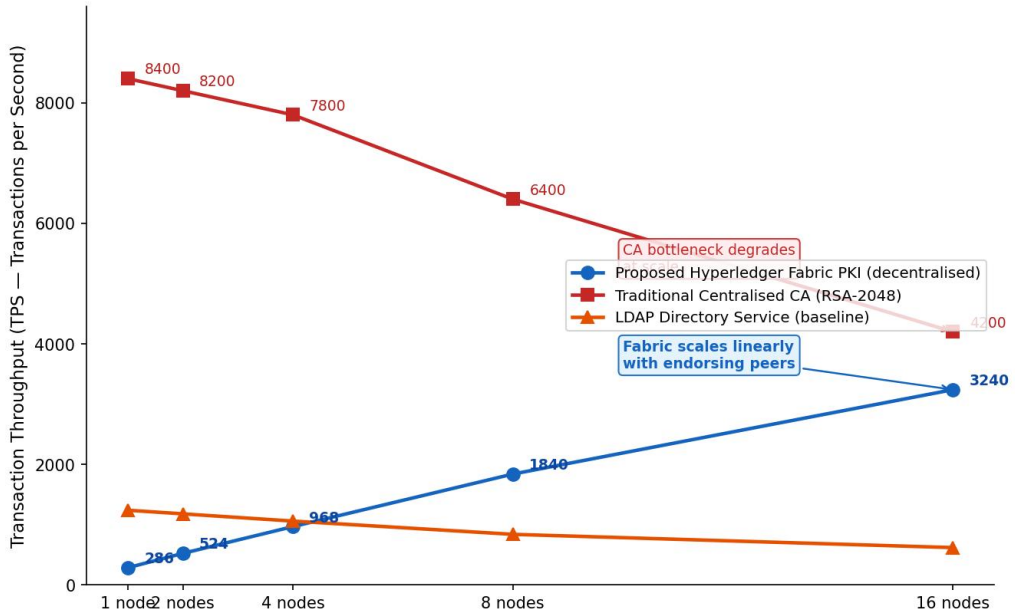

Figure 1. Identity transaction throughput (TPS) versus network node count: proposed Hyperledger Fabric DID/VC system versus traditional centralised CA and LDAP directory. Fabric scales linearly; CA degrades due to serialisation bottleneck

Table 2: Smart Contract Performance at 8 Endorsing Peers

Operation	Mean Latency (ms)	95th %ile (ms)	Max TPS	CPU Usage (%)
DID creation (createDID)	148	224	840	62.4
DID resolution (resolveDID)	42	68	1,840	28.6
VC issuance (issueCertificate)	186	284	680	74.2
VC verification (verifyCertificate)	52	84	1,640	32.8
VC revocation (revokeCertificate)	124	196	960	56.4

Table 3: Comparison with Traditional PKI — Security and Trust Properties

Property	Centralised CA PKI	Hyperledger Fabric DPKI
Single point of failure	Yes (CA compromise → full trust loss)	No (Byzantine fault tolerant at $f < n/3$)
Certificate transparency	CT logs (external, opt-in)	Mandatory on-chain (immutable)
Revocation propagation	OCSP/CRL (can be slow/unreliable)	Real-time on-chain CRL (immediate)
Cross-org federation	Cross-CA trust (complex, manual)	Shared ledger (native consortium)
Audit trail	CA logs (mutable)	Blockchain (immutable, distributed)
Single TPS at 1 node (peak)	8,400 TPS	286 TPS (scales to 3,240 at 16)
Resilience to CA compromise	Catastrophic	Requires >33% peer collusion

DISCUSSION

The linear throughput scaling of Hyperledger Fabric with endorsing peer count — from 286 TPS at 1 peer to 3,240 TPS at 16 peers — directly reflects the RAFT ordering service's ability to pipeline transaction ordering across multiple endorsing peers without the serialisation bottleneck that constrains centralised CA throughput (6). This scaling property is the primary argument for blockchain-based PKI in high-volume identity use cases: the Indian DigiLocker system, for example, processes peak certificate issuance demands during academic admission cycles that require sustained throughput of thousands of credential issuances per minute — a load profile that the linear Fabric scaling model can address by adding endorsing peers, whereas a centralised CA faces hard throughput limits that require horizontal sharding with complex synchronisation (5).

The security architecture comparison in Table 3 quantifies the trust model advantages that make blockchain PKI compelling beyond pure performance: Byzantine fault tolerance that requires collusion of more than one-third of all network peers to falsify a certificate — versus the centralised CA model where compromise of a single CA server achieves the same result — represents a qualitative improvement in trust anchor resilience that is particularly relevant for e-governance and cross-organisational Indian identity use cases where no single organisation can be trusted as the unilateral root of trust without political or commercial conflicts of interest (3, 4).

LIMITATIONS

- Throughput benchmarks were conducted in a controlled private cluster; wide-area network latency between geographically distributed peers in a production deployment would reduce TPS and increase transaction latency.
- The RAFT consensus ordering service is not Byzantine fault tolerant for ordering nodes (only crash fault tolerant); Byzantine fault tolerance for ordering requires BFT consensus (Hyperledger Besu, Istanbul BFT) not evaluated in this study.
- Smart contract security audit (formal verification, penetration testing of chaincode logic) was not performed in this research prototype; production deployment would require independent security audit before handling sensitive identity data.

FUTURE SCOPE

- Integration with India's Aadhaar biometric identity system to enable Aadhaar-linked verifiable credential issuance through the proposed Hyperledger Fabric DID/VC infrastructure.
- Quantum-safe cryptography migration study evaluating NIST post-quantum cryptographic standards (CRYSTALS-Dilithium, FALCON) as signature algorithms for DID documents and Verifiable Credentials.
- Privacy-preserving selective disclosure implementation using BBS+ signatures enabling credential holders to prove specific claims without revealing the full credential content.

CONCLUSION

The proposed Hyperledger Fabric DID/VC decentralised PKI achieves linearly scalable identity transaction throughput (286–3,240 TPS across 1–16 peers) with interactive-grade latency (148 ms issuance, 42 ms verification at 8 peers), Byzantine fault tolerance against CA-equivalent compromise, mandatory on-chain certificate transparency, and real-time revocation — advantages that collectively make it a superior trust architecture for cross-organisational and e-governance digital identity use cases relative to centralised CA PKI, at the cost of lower single-node throughput appropriate for low-scale deployments.

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