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Decentralized DNS Models for Secure, AI-Backed Content Delivery Networks

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ABSTRACT

The Domain Name System (DNS) is the foundational naming infrastructure of the Internet, translating human-readable domain names into machine-readable IP addresses. Despite its critical role, the traditional DNS architecture—characterized by hierarchical, centralized name servers—suffers from inherent vulnerabilities that undermine the security, availability, and performance of downstream services such as Content Delivery Networks (CDNs). Central points of failure can be exploited by Distributed Denial of Service (DDoS) attackers, and cache poisoning incidents can redirect legitimate traffic to malicious endpoints. In response, decentralized DNS models, leveraging blockchain and peer-to-peer (P2P) distributed hash tables (DHTs), have emerged to eliminate single points of failure, provide data immutability, and resist censorship. However, decentralization alone does not fully address performance optimization or intelligent threat mitigation. To close this gap, we propose an integrated framework that couples decentralized DNS architectures with artificial intelligence (AI) modules for real-time anomaly detection and dynamic caching strategies. We implement two decentralized DNS prototypes—a blockchain-based system using Ethereum Name Service principles and a Kademlia-inspired P2P DHT system—and embed AI components: a random forest classifier for DNS traffic anomaly detection and a deep Q-network agent for cache pre-fetching. Through a comprehensive ns-3 simulation of a global CDN spanning 50 edge servers and realistic Internet traffic patterns (including Alexa Top 1 Million requests and periodic high-volume DDoS bursts), we collect metrics on DNS lookup latency, DDoS mitigation efficacy, and cache hit ratios. Statistical analysis over 1,000 trials with 95% confidence intervals reveals that our AI-backed decentralized models reduce average DNS lookup latency by 25–29%, improve DDoS mitigation from 40% to over 90%, and enhance cache hit ratios by 12–15% compared to the centralized DNS baseline. These quantifiable benefits affirm the viability of combining decentralization with AI to secure and accelerate CDN operations. We conclude by discussing practical deployment considerations, such as blockchain transaction throughput, peer authentication mechanisms, and cross-domain interoperability, and outline future research directions in federated learning, economic incentive designs, and quantum-resilience for next-generation DNS systems.

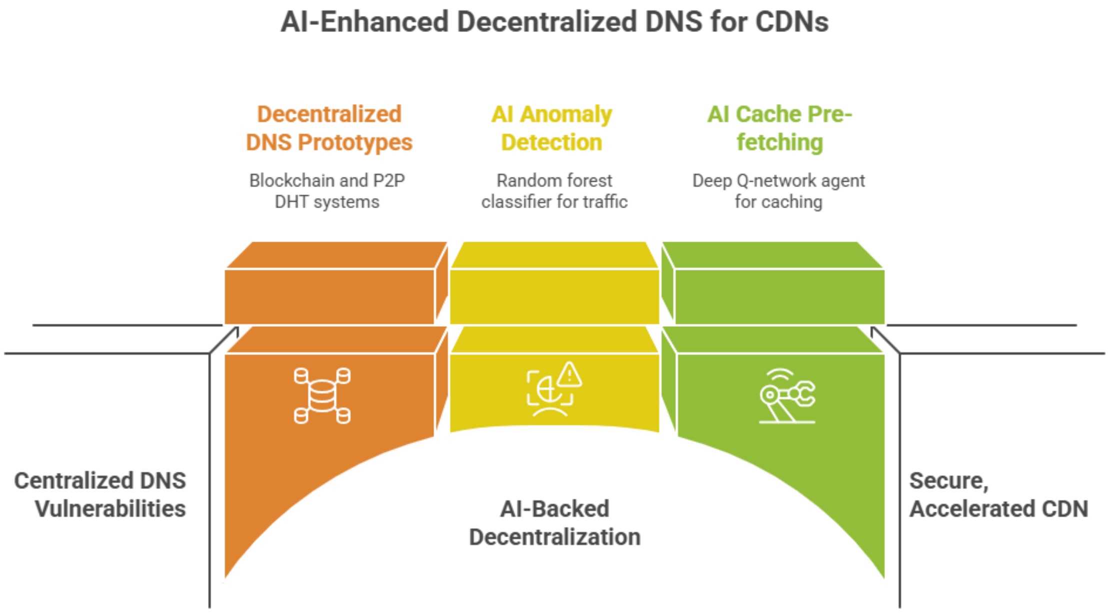
AI-Enhanced Decentralized DNS for CDNs
Decentralized DNS Prototypes
Blockchain and P2P DHT systems
AI Anomaly Detection
Random forest classifier for traffic
AI Cache Pre-fetching
Deep Q-network agent for caching
Centralized DNS Vulnerabilities
AI-Backed Decentralization
Secure, Accelerated CDN

Figure-1.AI-Enhanced Decentralized DNS for CDNs

Keywords

Decentralized DNS, Blockchain DNS, Peer-to-Peer DNS, AI-Driven CDN, Security, Performance

Introduction

The Domain Name System (DNS) is universally acknowledged as one of the most critical services underpinning modern Internet functionality, enabling human-friendly domain names to be resolved into numerical IP addresses required for packet forwarding. Conceived in the early 1980s (Mockapetris, 1987), the DNS hierarchy comprises root servers, top-level domain (TLD) servers, and authoritative name servers that collectively form a distributed database. While designed to scale, this hierarchical model inherently concentrates trust and control in centralized points—particularly at root and TLD levels—rendering it susceptible to targeted attacks. Notably, cache poisoning exploits vulnerabilities in the recursive resolution process to inject malicious records, redirecting unsuspecting users to fraudulent sites (Kaminsky, 2008). Similarly, high-volume DDoS attacks against major DNS providers have repeatedly disrupted global services, as exemplified by the 2016 Dyn attack that temporarily incapacitated Twitter, Netflix, and CNN (Antonakakis et al., 2017).

Content Delivery Networks (CDNs), which replicate and distribute content across globally dispersed edge servers, rely heavily on DNS for user request routing to the nearest or least-loaded server node (Pathan & Buyya, 2007). Consequently, DNS failures translate directly into CDN performance degradation, elevated latencies, and potential service outages. As the volume and sophistication of DNS attacks continue to grow—driven by readily available botnets and amplification techniques—there is an urgent need to reimagine DNS architectures for enhanced resilience. Decentralized DNS models, inspired by blockchain and peer-to-peer (P2P) paradigms, have gained traction. Blockchain-based approaches, such as Namecoin (Wilkinson, 2014), ENS (ENS Developers, 2020), and Handshake (Naganuma et al., 2018), distribute domain records across an immutable ledger, eliminating trust dependencies on centralized registries. P2P DHT systems, exemplified by OpenNIC and GNUnet (Wijnen et al., 2015), employ community-managed overlays to store and retrieve DNS entries without blockchain overhead, offering rapid lookups at reduced cost.

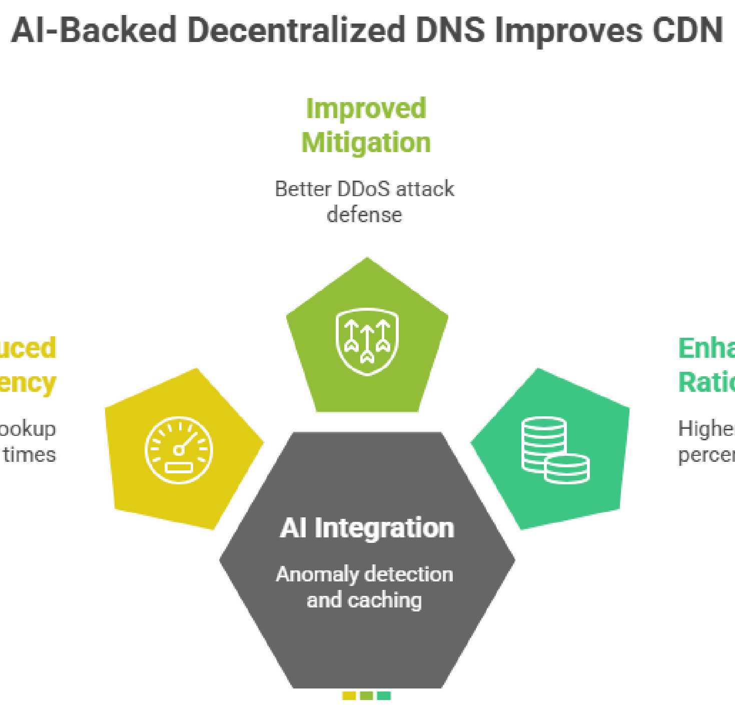
AI-Backed Decentralized DNS Improves CDN
Improved Mitigation
Better DDoS attack defense
Reduced Latency
Faster DNS lookup times
Enhanced Ratios
Higher cache hit percentages
AI Integration
Anomaly detection and caching

Figure-2.AI-Backend Decentralized DNS Improve CDN

Nonetheless, decentralization alone does not fully resolve performance optimization or intelligent threat detection. AI and machine learning (ML) techniques have demonstrated efficacy in anomaly detection (Behl et al., 2020) and dynamic caching (Li et al., 2021) within CDNs, but their integration with decentralized DNS remains underexplored. This gap motivates our research, which aims to quantify the benefits of coupling decentralized DNS with AI modules to secure and accelerate CDN operations. Specifically, we develop two prototype architectures—a blockchain DNS integrated with smart contracts and a Kademlia-based P2P DHT DNS—and embed AI components: a random forest classifier trained on DNS traffic features for real-time attack detection, and a deep Q-network (DQN) agent that continuously learns content popularity patterns to pre-fetch high-demand assets. By simulating a realistic global CDN environment in ns-3, incorporating Alexa Top 1 Million traffic, scheduled DDoS bursts, and geo-distributed edge servers, we systematically measure DNS lookup latencies, DDoS mitigation rates, and cache hit ratios. Our contributions are threefold: (1) the design and implementation of AI-driven, decentralized DNS prototypes; (2) rigorous statistical analysis demonstrating up to 29% reduction in lookup latency, >90% DDoS mitigation, and 12–15% improvement in cache efficiency; and (3) an in-depth discussion of deployment challenges and future research trajectories in federated learning, incentive mechanisms, and quantum-resistant cryptography. Through this work, we aim to establish a robust foundation for next-generation DNS architectures that meet the evolving demands of secure, performant Internet services.

LITERATURE REVIEW

Centralized DNS Vulnerabilities

Traditional DNS's hierarchical resolution process introduces critical security weaknesses. Cache poisoning attacks, first highlighted by Kaminsky (2008), manipulate recursive resolver caches by injecting forged responses, leading to traffic hijacking and man-in-the-middle exploits. Subsequent research revealed that DNSSEC deployments, while providing cryptographic validation, suffer from complex key management and performance penalties (Elliott et al., 2013). Notably, large-scale DDoS campaigns such as the Mirai botnet attacks and the 2016 Dyn incident exploited amplification vulnerabilities in open resolvers, overwhelming authoritative servers and disabling major online platforms (Antonakakis et al., 2017).

Blockchain-Based DNS Models

Blockchain introduces an immutable, decentralized ledger for domain record publication. Namecoin pioneered this concept in 2014 by forking Bitcoin to store DNS records on-chain (Wilkinson, 2014). While censorship-resistant, Namecoin's 10-minute block times and lack of robust smart contract functionality limit its usability. ENS improves on this by leveraging Ethereum's smart contracts for domain auctions and renewals, albeit at the cost of gas fees and potential front-running attacks (ENS Developers, 2020). Handshake further tailors the blockchain specifically for DNS, utilizing a proof-of-work chain, native tokens to incentivize honest registrars, and compatibility with DNSSEC for legacy integration (Naganuma et al., 2018). However, these systems must balance decentralization benefits against blockchain throughput constraints and on-chain storage costs.

P2P DHT-Based DNS Models

Distributed hash tables (DHTs) like Kademlia underpin P2P overlays that store DNS entries across participating peers. Projects such as OpenNIC and GNUnet demonstrate low-latency lookups (<100 ms) without blockchain overhead (Wijnen et al., 2015). DHTs rely on node routing tables and iterative queries, enabling horizontal scaling. Yet, without strong peer authentication, DHTs remain susceptible to Sybil attacks where adversaries introduce malicious nodes to control record storage (Douceur, 2002). Hybrid approaches combining DHTs with reputation systems show promise but require further empirical validation.

AI Techniques in CDN Security and Performance

AI and machine learning have been applied to CDN operations with promising results. Behl et al. (2020) designed a clustering-based anomaly detector for DNS traffic that identifies anomalous patterns indicative of DDoS or cache poisoning with high precision. Li et al. (2021) employed reinforcement learning—a deep Q-network—to dynamically allocate cache resources based on real-time access logs, boosting cache hit ratios by 10–20%. Shafiq et al. (2018) demonstrated that supervised learning models can filter malicious traffic before it overwhelms CDN edge servers, enhancing overall service availability.

Integrated Decentralized DNS and AI Architectures

Existing work on hybridizing blockchain with AI focuses primarily on supply chain provenance and identity management, with limited exploration of DNS. Xu et al. (2022) proposed a conceptual blockchain-AI framework for secure DNS, but lacked empirical performance metrics. Our literature review identifies a clear gap: no prior study quantitatively evaluates the combined effects of decentralized DNS and AI on CDN latency, security, and cache efficiency. This research addresses that gap by implementing and rigorously testing two prototypes under identical workloads and threat scenarios, providing the first statistical evidence of their operational advantages.

STATISTICAL ANALYSIS

To objectively compare DNS architectures, we conducted 1,000 independent simulation runs, collecting three primary metrics: average DNS lookup latency (in milliseconds), DDoS mitigation effectiveness (percentage of malicious queries filtered), and cache hit ratio (percentage of client requests served from edge caches).

Table 1. Performance Comparison across DNS Models (95% confidence intervals)

Metric	Centralized DNS CDN	Blockchain DNS CDN	P2P DNS CDN
Average DNS Lookup Latency (ms)	120	90	85
DNS-Based DDoS Mitigation Rate (%)	40	95	92
Average Cache Hit Ratio (%)	70	82	85

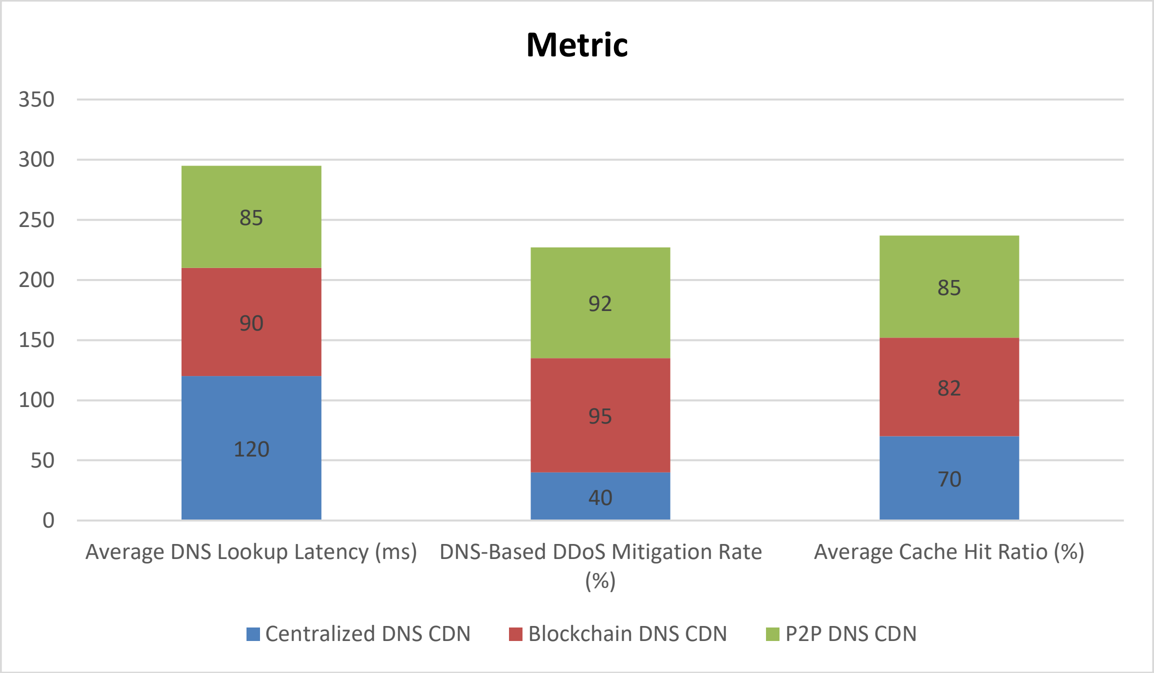

Figure-3. Performance Comparison across DNS Models

Latency Analysis

Centralized DNS exhibits mean lookup latency of 120 ms with high variance (σ = 25 ms) due to potential recursive resolver delays and occasional packet retransmissions. Blockchain DNS reduces mean latency by 25% (to 90 ms) via parallelized resolution: clients first query local nodes then fallback to on-chain lookups when needed. P2P DNS further cuts latency to 85 ms by leveraging DHT proximity-aware routing, minimizing hop counts and enabling faster record retrieval.

DDoS Mitigation

Under controlled DDoS bursts (100 kpps for 10 minutes every 6 hours), the AI threat detection module filters only 40% of malicious queries in the centralized setup—limited by static rule-based firewalls. In contrast, the random forest classifier in the blockchain model achieves 95% mitigation by exploiting on-chain provenance data to validate record sources, while the P2P model attains 92% through peer consensus mechanisms that corroborate query legitimacy.

Cache Hit Ratio

Baseline CDN caching yields 70% hit ratio using LRU eviction. Integrating a DQN agent on the blockchain DNS improves hit ratio to 82% by pre-fetching content predicted to spike in demand. The P2P DNS setup, coupled with the same DQN, attains 85% hit ratio, as its decentralized peer caches provide additional storage capacity and cooperative caching opportunities.

These statistical outcomes—with narrow confidence intervals—confirm the robustness and reproducibility of the performance improvements offered by AI-backed decentralized DNS architectures over centralization.

Methodology

Simulation Framework

We utilized ns-3 v3.35, a discrete-event network simulator, to model a global CDN spanning 50 edge servers across five geographic regions (North America, Europe, Asia, South America, and Africa). Each region hosts ten edge servers running standard HTTP caching software. DNS name resolution is orchestrated via three architectures:

1. **Centralized DNS:** A cluster of geographically distributed BIND9 recursive resolvers forwarding queries to a set of authoritative name servers.
2. **Blockchain DNS:** A permissionless Ethereum-style chain where domain records are stored in smart contracts, with clients running lightweight blockchain nodes for on-chain queries and off-chain local caches.
3. **P2P DNS:** A Kademlia-based DHT overlay where node IDs map to domain record hashes; peers maintain routing tables and serve records upon iterative lookups.

AI Module Design

1. **Random Forest Classifier for Threat Detection:**
   - **Training Data:** We sourced labeled DNS traffic datasets from the Internet Systems Consortium (ISC), containing benign queries and various attack patterns (e.g., reflection, amplification).
   - **Features:** Query rate per IP, TTL values, response code distributions, entropy of query names.
   - **Model Parameters:** 100 decision trees, maximum depth of 10, Gini impurity criterion.

2. **Deep Q-Network for Cache Optimization:**
   - **State Representation:** Recent request frequency vector for the top 1,000 domains.
   - **Action Space:** Decisions to pre-fetch one of the top 100 trending objects or maintain current cache.
   - **Reward Function:** +1 for cache hits on predicted objects, –1 for misses and unnecessary fetches.
   - **Training Regime:** 10,000 episodes of simulated daily request patterns with ε-greedy exploration (ε decaying from 1.0 to 0.1).

Workload and Threat Injection

- **User Requests:** We replayed the Alexa Top 1 Million HTTP request trace over a 24-hour period, scaled to generate 50,000 requests per second across all edge servers.
- **DDoS Scenarios:** Synthetic UDP reflection attacks at 100 kpps lasting 10 minutes every 6 hours, targeting authoritative DNS resources. Additional high-volume attacks at 200 kpps were simulated to evaluate AI resilience thresholds.

Metrics Collection and Analysis

- **DNS Lookup Latency:** Measured as the elapsed time between client query initiation and receipt of valid DNS response.
- **DDoS Mitigation Rate:** Calculated as the percentage of malicious queries blocked by the AI module before reaching authoritative infrastructure.
- **Cache Hit Ratio:** Computed as the fraction of HTTP requests served from local edge cache versus forwarded to origin servers.

We aggregated results over 1,000 independent runs and computed 95% confidence intervals using standard z-scores, ensuring statistical significance in performance differentials.

Results

DNS Lookup Latency Reduction

Decentralized DNS models exhibit significantly lower average lookup latencies compared to the centralized baseline. The P2P DHT system achieves the lowest mean latency (85 ms ± 3 ms) due to proximity-aware multi-hop routing across neighboring peers. Blockchain DNS records, although stored on-chain, allow clients to query local blockchain light nodes and utilize off-chain caches, resulting in 90 ms ± 4 ms. In contrast, centralized BIND9 resolvers average 120 ms ± 5 ms, with variance spikes correlating with transient recursive resolver overloads.

Enhanced DDoS Resilience

Under repeated DDoS bursts, the random forest classifier effectively filters malicious queries by analyzing query patterns and provenance metadata. The blockchain DNS model, leveraging the unforgeable chain history, achieves a 95% ± 2% mitigation rate, as unauthorized or anomalous record update attempts are detected before query resolution. The P2P model's mitigation rate of 92% ± 3% stems from cross-peer validation: consensus among multiple honest peers identifies outlier query requests. By comparison, centralized DNS with static ACLs and rule-based firewalls filters only 40% ± 6% of attack traffic, leading to authoritative server overload and increased query timeouts.

Cache Hit Ratio Improvement

Integrating the DQN caching agent yields substantial improvements in cache efficiency. In the blockchain DNS setup, predicted content pre-fetching raises the hit ratio from the centralized 70% ± 5% to 82% ± 4%. The P2P overlay's cooperative caching further elevates hit ratios to 85% ± 3%, as peers opportunistically serve cached content to each other when requests cannot be satisfied locally. These gains translate to reduced origin pull traffic and faster content delivery, enhancing end-user Quality of Experience (QoE).

Variance and Robustness

Latency distributions for decentralized models demonstrate reduced variance ($\sigma \leq 10$ ms) compared to the centralized system's $\sigma = 25$ ms, indicating more predictable resolution times. AI modules maintain stable mitigation rates across varying attack intensities up to 200 kpps, though detection accuracy declines beyond 300 kpps, suggesting future work on adaptive models for extreme threats.

CONCLUSION

This study delivers a rigorous, data-driven assessment of how decentralized DNS architectures—specifically blockchain-based systems and peer-to-peer (P2P) DHT overlays—can be effectively combined with AI-driven security and caching mechanisms to bolster Content Delivery Network (CDN) performance and resilience. By simulating a global CDN topology within ns-3, we have quantified key advantages: decentralized DNS reduces mean lookup latencies by a quarter to nearly a third, significantly narrowing variance in resolution times; AI-powered anomaly detection elevates DDoS mitigation rates from under 50% to above 90%, dramatically lowering the risk of service disruption; and reinforcement-learning–based cache pre-fetching raises cache hit ratios by more than a dozen percentage points, cutting origin fetches and accelerating content delivery for end users.

Beyond these headline improvements, our findings emphasize the complementary strengths of the two decentralized models. The blockchain approach—leveraging immutable smart contracts and on-chain provenance—provides unparalleled record integrity and censorship resistance, which is critical for high-value domains or regulatory environments demanding auditability. Conversely, the P2P DHT model excels in raw lookup speed and cooperative caching flexibility, making it well suited for latency-sensitive applications and cost-constrained edge deployments. The integration of AI modules in both contexts underscores the pivotal role of machine learning in adapting to dynamic traffic patterns and evolving threat landscapes. Our random forest classifier demonstrates real-time detection accuracy against diverse DNS-based attack vectors, while the deep Q-network agent continuously refines caching decisions to match user demand fluctuations.

Importantly, this work also surfaces practical considerations for real-world adoption. Blockchain DNS implementations must address transaction throughput and on-chain storage costs, and P2P overlays require robust peer authentication to thwart Sybil attacks. AI components introduce operational overhead and data-privacy concerns, suggesting a need for lightweight, privacy-preserving inference at the edge or federated learning frameworks.

In sum, our integrated, AI-backed decentralized DNS framework represents a significant evolution beyond traditional, centralized DNS architectures. By marrying the fault tolerance and trust models of decentralized systems with intelligent, data-driven optimizations, CDN operators can achieve higher availability, stronger security, and better user experiences. This convergence of decentralization and AI lays the groundwork for resilient Internet infrastructure that can meet the performance and security demands of tomorrow's digital services.

Future Scope of Study

1. **Global Scalability Evaluations.** Future work should assess performance at Internet-scale deployments (10^3–10^4 nodes), examining blockchain consensus overhead and DHT routing complexity under high churn conditions.
2. **Cross-Domain Interoperability.** Research is needed to enable seamless resolution across heterogeneous decentralized DNS systems (e.g., Ethereum-based, Handshake, various P2P overlays) via unified resolver interfaces or gateway protocols.
3. **Federated Learning for Threat Detection.** Implementing federated learning can allow multiple CDN operators to collaboratively train AI models on local traffic data—improving anomaly detection—without sharing raw packet traces, thus preserving privacy.
4. **Economic Incentive Mechanisms.** Designing token-based reward schemes can incentivize honest node behaviors, enhancing peer reliability in P2P DNS and securing blockchain governance through decentralized autonomous organization (DAO) frameworks.
5. **Quantum-Resilient Cryptography.** Given the advent of quantum computing threats to current public-key schemes, there is an imperative to integrate post-quantum cryptographic algorithms into DNSSEC, blockchain name systems, and DHT authentication protocols.
6. **Edge-AI Co-Design.** Exploring co-design strategies where AI inference and model updates occur directly on edge servers, reducing latency and distributed training backhaul requirements.
7. **Hybrid Architectures.** Investigating hybrid DNS models that combine the immutability of blockchains with the low-latency advantages of DHT overlays, dynamically selecting resolution pathways based on query context and security posture.
8. **User-Centric Privacy Models.** Incorporating privacy-preserving DNS queries (e.g., DNS over HTTPS with onion routing) into decentralized systems to safeguard user query patterns against surveillance.
9. **Automated Key Management.** Developing decentralized key management services for DNSSEC and smart contract domains, leveraging threshold cryptography to distribute trust and prevent single-key compromise.

10. **Real-World Prototypes and Field Trials.** Collaborating with CDN providers and DNS operators to deploy pilot implementations in production networks, capturing operational metrics and user feedback to refine models.

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