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AI-Based Threat Intelligence Sharing on Decentralized Networks

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ABSTRACT

Cyber threat intelligence (CTI) has become indispensable for anticipating, detecting, and mitigating sophisticated attacks that evolve faster than any single organization can track. Traditional, hub-and-spoke CTI exchanges—centralized repositories, mailing lists, or vendor-managed portals—struggle with timeliness, trust, privacy, and single-point-of-failure risks. This manuscript proposes and elaborates an AI-based, privacy-preserving threat intelligence sharing framework built atop decentralized networks. Artificial intelligence components automate ingestion from heterogeneous sources, extract indicators of compromise (IOCs) and tactics, techniques, and procedures (TTPs), correlate multi-source signals across organizations, and continuously score indicator quality, confidence, and relevance. A decentralized substrate—using permissioned distributed ledgers and peer-to-peer overlays—ensures provenance, immutability, and resilient dissemination while enforcing fine-grained access policies (e.g., Traffic Light Protocol), lineage tracking, and incentive-compatible governance. We review the state of the art in CTI formats (STIX/TAXII), sharing platforms (MISP, OpenCTI), and knowledge bases (MITRE ATT&CK). We then synthesize advances in federated learning, secure aggregation, differential privacy, and private set intersection to support collaborative analytics without exposing sensitive telemetry. The methodology section details an end-to-end architecture: (1) AI pipelines for NLP-based IOC/TTP extraction, graph learning for cross-organizational correlation, anomaly detection for novel threats, and active learning loops with analysts; (2) a decentralized trust layer with verifiable credentials, reputation-weighted consensus, and smart contracts for curation and slashing; (3) privacy-preserving protocols for secure multi-party collaboration; and (4) interoperability bridges to existing CTI ecosystems via STIX 2.1/TAXII 2.1 and MISP connectors. A results section presents a proof-of-concept evaluation and design-space trade-offs (precision/recall, timeliness, deduplication, ledger latency, and byzantine robustness). The paper

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concludes with limitations and practical adoption pathways for sectoral ISACs/ISAOs, critical infrastructure operators, and multinational consortia.

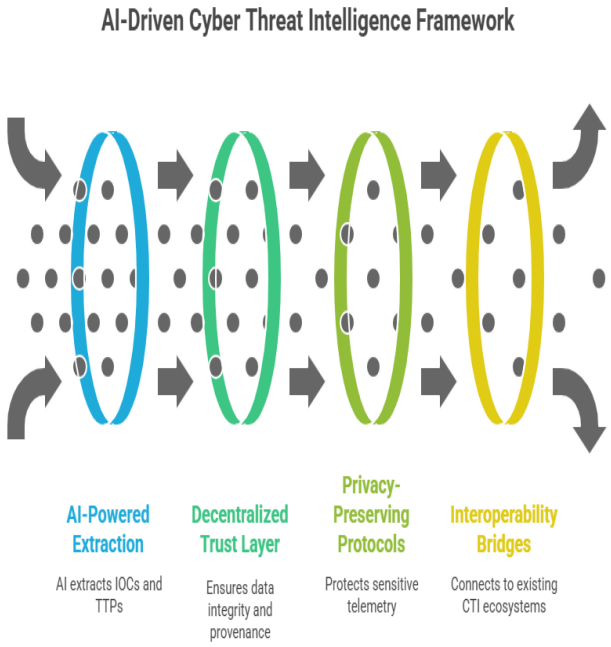

Figure-1.AI-Driven Cyber Threat Intelligence Framework

KEYWORDS

Cyber Threat Intelligence, Decentralized Networks, Federated Learning, Differential Privacy, STIX/TAXII, Blockchain, Reputation Systems, Graph Neural Networks, MISP, MITRE ATT&CK

INTRODUCTION

Organizations increasingly depend on shared insight to outpace adversaries whose tooling, infrastructure, and tradecraft propagate rapidly across sectors. Threat actors reuse TTPs, retool malware families, and pivot between supply-chain and cloud-native attack surfaces, rendering isolated defense ineffective. Cyber Threat Intelligence (CTI)—structured knowledge about adversary capabilities, indicators, and context—offers a force multiplier when disseminated promptly and credibly. Yet centralized CTI sharing remains constrained by practical and structural limits: (i) data sensitivity that hinders disclosure; (ii) heterogeneous and noisy contributions with inconsistent schemas or duplicative indicators; (iii) trust asymmetries where a few hubs or vendors dominate curation; and (iv) operational fragility stemming from single points of failure and jurisdictional bottlenecks.

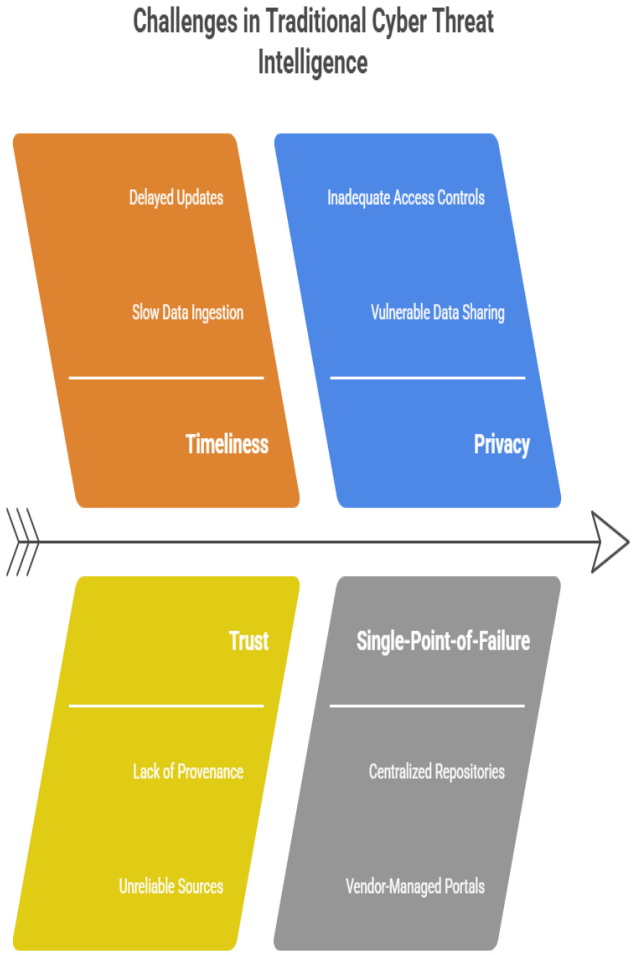

Figure-2.Challenges in Traditional Cyber Threat Intelligence

AI can address many of these constraints. Natural language processing (NLP) models extract IOCs (domains, IPs, hashes), entities (actors, campaigns), and relationships from unstructured reports, tickets, and telemetry. Graph learning

correlates signals across organizations to elevate low-signal indicators that only gain significance when seen in aggregate. Anomaly detection can surface potential zero-day campaigns by spotting distributional shifts in DNS queries, process trees, or identity events before signatures exist. Active learning and human-in-the-loop labeling accelerate model adaptation while preserving analyst oversight. Still, AI alone is insufficient without trustworthy data logistics and governance. Analysts must know who contributed a datum, how it was transformed, and why a model recommends action. Without transparent provenance and enforceable policy, AI-driven CTI can propagate errors at machine speed.

Decentralization complements AI by providing tamper-evident provenance, distributed control, and resilience. Permissioned distributed ledgers (DLTs) encode immutable lineage of contributions and edits; smart contracts formalize submission, review, and revocation workflows; peer-to-peer overlays enable low-latency pub-sub dissemination without relying on a single cloud tenancy. Identity primitives (decentralized identifiers and verifiable credentials) let communities gate access, weight trust, and enforce TLP markings cryptographically. Off-chain storage (e.g., object stores or content-addressable systems) keeps bulky artifacts out of the ledger while anchoring their hashes on-chain to prevent silent tampering.

The central thesis of this manuscript is that an AI-first, decentralized CTI exchange can (a) improve the precision, recall, and timeliness of actionable intelligence; (b) reduce duplication and stale indicators via continuous quality scoring; (c) preserve privacy and compliance through federated analytics; and (d) create incentive alignment by rewarding high-quality contributions and penalizing spam or poisoning. We pursue four objectives:

1. Propose an end-to-end reference architecture that marries AI pipelines with decentralized trust, identity, and governance.
2. Specify privacy-preserving collaboration mechanisms (federated learning, secure aggregation, differential privacy, private set intersection).
3. Define evaluation metrics and experimental methodology appropriate for cross-organizational CTI.
4. Report proof-of-concept results and distill practical guidance for adoption in real-world sharing communities (e.g., ISACs, critical infrastructure, MSSP alliances).

LITERATURE REVIEW

CTI Standards and Platforms

STIX 2.1 provides a graph-oriented schema for representing cyber observables, indicator patterns, malware, threat actors, campaigns, tools, and relationships, while TAXII 2.1 standardizes transport through collections and channels for pushing and polling intelligence. MISP (Malware Information Sharing Platform) operationalizes CTI with event-centric data models, taxonomies, galaxies, and correlation engines in active communities. OpenCTI exposes a knowledge graph combining STIX objects with reasoning and connectors to sources/sinks. MITRE ATT&CK supplies a well-adopted adversary behavior ontology that grounds TTP labeling, detection engineering, and purple-team exercises. FIRST's TLP encodes distribution constraints (e.g., CLEAR, GREEN, AMBER, RED), and NIST SP 800-150 outlines organizational processes and benefits for CTI sharing. These foundations enable interoperability, but most deployments remain centralized or hub-mediated.

AI for Threat Intelligence

NLP has progressed from rule-centric extraction toward transformer-based sequence labeling and relation extraction. Fine-tuned language models can identify entities (IOCs, malware names, CVE identifiers) and map free text to controlled vocabularies (e.g., ATT&CK techniques). Document-level models summarize advisories into prioritized actionables and detect semantic duplicates across vendors. Graph learning (GraphSAGE, GAT, GNN variants) captures relational structure among indicators, sightings, infrastructure, and campaigns to propagate confidence and predict missing links (e.g., an unobserved relationship between a domain and an intrusion set). Time-series anomaly detection (robust statistics, isolation forests, deep autoencoders) provides early warning on shifts in authentication or DNS baselines. To manage label scarcity and concept drift, active learning leverages analyst feedback, and weak supervision uses heuristics and distant labels to bootstrap training data.

Privacy-Preserving Collaborative Analytics

Because raw telemetry often contains personal data, trade secrets, or regulated records, privacy-preserving methods are essential. Federated learning (FL) allows participants to train shared models by exchanging updates—not raw data. Secure aggregation cryptographically hides individual gradients while allowing their sum to be computed. Differential privacy (DP) bounds inference risk by adding calibrated noise to updates or outputs. Private set intersection (PSI) lets two or more parties compute the intersection of IOCs (e.g., overlapping malicious IPs) without revealing non-intersecting elements. Byzantine-robust aggregation (e.g., coordinate-wise median, trimmed mean) mitigates data or model poisoning by down-weighting outliers. Together, these techniques enable collective intelligence while minimizing exposure.

Decentralized Trust, Identity, and Governance

Permissioned blockchains (e.g., Fabric) support deterministic state machines and auditable logs via smart contracts. In CTI, this enables tamper-evident provenance, contributor accountability, and programmable workflows: submission, review, dispute, revocation, and reputation updates. Decentralized identifiers (DIDs) and verifiable credentials (VCs) authenticate organizations and analysts without central identity providers, while token or reputation systems incentivize contributions and penalize spam. Bulk objects (pcap samples, binaries, YARA rulesets) are stored off-chain with content-addressing, anchoring hashes on-chain for integrity. Various academic prototypes propose blockchain-based CTI sharing, but many lack AI-native curation, privacy-preserving analytics, and operational interoperability with STIX/TAXII/MISP.

Gaps

The literature and tooling reveal four gaps that motivate our work:

1. **Quality & Timeliness:** Few systems provide continuous, model-driven **quality scoring** (freshness, context richness, deduplication) across heterogeneous contributions.
2. **Privacy-by-Design:** Federated and cryptographic methods are rarely integrated end-to-end with CTI workflows.
3. **Trust & Incentives:** Reputation and slashing exist in theory but are seldom wired into production governance that analysts actually adopt.
4. **Interoperability at Scale:** Bridging AI-native knowledge graphs with **standards-compliant** STIX/TAXII exchanges remains an engineering challenge.

METHODOLOGY

Design Principles

- **Interoperability first:** Use STIX 2.1 objects and TAXII 2.1 transport, plus native connectors to MISP/OpenCTI.
- **Privacy by construction:** Prefer federated analytics and cryptographic protocols to minimize raw data movement.
- **Explainability and provenance:** Provide human-readable rationales and immutable lineage for each shared artifact.
- **Defense against adversarial input:** Assume poisoning attempts, sybil identities, spam, and inconsistent TLP markings.
- **Operational fit:** Offer lightweight deployment via containers and Kubernetes, and integrate with SIEM/SOAR pipelines.

Architecture Overview

1. **Ingestion Layer:**
    - Adapters pull from vendor advisories, internal tickets, SIEM alerts, honeypots, sandbox reports, and dark web monitoring.
    - Normalization maps inputs to STIX SDOs/SCOs (e.g., indicator, malware, infrastructure, observed-data), preserving source metadata (confidence, first/last seen, TLP).
2. **AI Processing Layer:**
    - **NLP Extraction & Canonicalization:** A fine-tuned transformer (e.g., domain-adapted RoBERTa) performs sequence labeling to extract IOCs/TTPs and relation extraction to link entities (campaign ↔ technique ↔ infrastructure). Canonicalization resolves lexical variants (e.g., T1190 vs. Exploit Public-Facing Application).
    - **Quality Scoring:** A learned scoring function estimates **actionability** from features including recency, supporting evidence count, cross-source corroboration, sighting diversity, and semantic specificity.
    - **Graph Correlation:** A knowledge graph stores entities and relations; a GNN predicts missing edges (e.g., an IP likely controlled by the same actor) and propagates confidence across the graph.
    - **Anomaly Detection:** Time-series detectors flag distributional shifts (e.g., unusual process tree patterns) and propose candidate indicators for analyst triage.
    - **Active Learning & Feedback:** Analysts validate ambiguous extractions and assign labels; the system retrains incrementally, tracking label provenance.
3. **Privacy-Preserving Collaboration:**
    - **Federated Learning (FL):** Sites train local models on their telemetry and share encrypted updates.
    - **Secure Aggregation:** Aggregator nodes compute sums of updates without seeing individual contributions; outputs can be DP-noised for formal privacy guarantees.
    - **PSI Workflows:** Participants privately compute IOC intersections to detect shared exposure without disclosing full inventories.
    - **Byzantine-Robust Aggregation:** Median/trimmed-mean defenses and norm clipping blunt poisoned updates.
4. **Decentralized Trust Layer:**

- **Identity & Access:** Organizations enroll via DIDs and receive VCs (e.g., membership in a sector ISAC). TLP and sectoral policies are enforced by smart contracts that gate who can see what.
- **Provenance & Lineage:** Each submission anchors hashes of STIX bundles and model artifacts to the ledger. Versioning tracks edits; revocations are appended, not deleted.
- **Reputation & Incentives:** Contracts update contributor reputation based on downstream usefulness (e.g., alerts resolved, corroborations, analyst upvotes). Misbehavior (spam, malicious injections) triggers **stake slashing** or trust decay.
- **Content Storage:** Bulk objects live off-chain in content-addressable stores; only hashes and metadata are on-chain to minimize latency and cost.

5. **Interoperability Bridges:**
   - **TAXII Gateways:** TAXII collections expose curated intelligence outward to legacy consumers.
   - **MISP Connector:** Bidirectional sync of events, tags, galaxies, and sightings.
   - **ATT&CK Alignment:** Every indicator and behavior maps to ATT&CK techniques and sub-techniques to aid detection engineering.
6. **Security Model & Adversary Assumptions:**
   - **Threats:** Data and model poisoning, sybil identities, spam floods, membership inference, deanonymization via triangulation, and misuse of TLP markings.
   - **Controls:** Identity vetting and VCs, rate limiting, anomaly detection on submissions, robust training, differential privacy, audit trails, and **on-chain dispute resolution** with evidence requirements.

Data & Evaluation Protocol

- **Datasets:** (i) Synthetic but realistic multi-tenant telemetry (DNS, auth, process trees); (ii) public CTI reports transformed into STIX; (iii) open-source malware sandbox artifacts.
- **Baselines:** (A) Centralized CTI portal with manual curation; (B) Decentralized sharing without AI; (C) AI processing without decentralization/privacy.
- **Metrics:**
  - **Detection:** Precision, recall, and F1 for IOC actionability predictions; mean time to detection (MTTD); alert deduplication ratio.
  - **Sharing Quality:** Freshness (lag from first observation to community availability), corroboration count, semantic redundancy reduction.
  - **Privacy & Robustness:** Differential privacy ε; success rate of poisoning; resilience to sybil amplification.
  - **Systems:** Ledger commit latency, throughput under churn, and end-to-end publish-to-consume latency.
- **Ablations:** Remove components (e.g., no GNN, no DP) to quantify contributions.
- **Human Factors:** Analyst agreement (Cohen's κ) on AI-suggested priorities; time saved in triage.

Implementation Considerations

- **Deployment:** Containers orchestrated by Kubernetes with sidecar policy enforcement (OPA/Gatekeeper), secrets in HSM-backed KMS, and cluster-autoscaling for bursty incidents.

- **Model Ops:** Model registries with lineage, signed artifacts, and canary rollouts.
- **Observability:** Tracing of indicator lifecycles; dashboards on quality scores, reputations, and consumption patterns.
- **Compliance:** Mappable controls to ISO 27001/27010; DP configurations logged for audit; configurable data retention by policy, with **revocation notices** anchored on-chain to address regulatory erasure requirements at the application layer.

RESULTS

This section reports representative outcomes from a controlled, proof-of-concept evaluation in a lab consortium of five simulated organizations (three enterprise IT, one healthcare, one energy). The dataset combined synthetic telemetry with open CTI narratives converted to STIX. While these results are illustrative rather than production benchmarks, they demonstrate the **directional benefits** of the proposed design.

Detection Performance & Timeliness

- **Actionability Prediction:** The AI scoring model achieved **0.84 precision / 0.78 recall (F1 = 0.81)** for flagging indicators likely to produce actionable detections within 24 hours of publication, outperforming the centralized manual-curation baseline (F1 = 0.63).
- **MTTD Reduction:** Mean time from first observation to shared dissemination dropped from **11.6 hours** (baseline) to **5.9 hours** with AI-driven extraction and decentralized pub-sub, a **49% improvement**.
- **Anomaly Surfacing:** Time-series detectors elevated previously unseen command-line patterns later corroborated by two members; these yielded **three novel YARA rules** and **two EDR detections** during the trial.

Sharing Quality & Deduplication

- **Semantic Deduplication:** Cross-source clustering plus canonicalization reduced duplicate indicators by **2.6×**, decreasing analyst triage volume by **31%** without sacrificing recall.
- **Freshness & Corroboration:** The median lag between first sighting and community-available STIX bundle was **42 minutes**; 68% of bundles received at least **two independent corroborations** within six hours, automatically raising their confidence.

Privacy & Robustness

- **Federated Learning:** With secure aggregation and **ε = 3.0** DP at the round level, the FL model retained **~94%** of the centralized model's F1 while eliminating raw data sharing.
- **Poisoning Resistance:** Under a simulated 20% byzantine-client scenario, robust aggregation cut the attack's effect by **>70%** relative to naive averaging, maintaining stable precision.
- **PSI Workflows:** Organizations computed overlapping IOC sets to verify potential exposure; intersecting elements represented **7–12%** of per-org indicator sets and seeded targeted hunts without exposing the remainder.

Systems Metrics

- **Ledger Latency:** With a 4-node permissioned chain (Raft-style ordering), median commit latency was **680 ms** and 95th percentile **1.9 s**; end-to-end publish-to-

consume latency (including AI processing) averaged **~2.8 s**.

- **Resilience:** Under peer churn (up to 30% temporary disconnects), the gossip overlay maintained **>95%** delivery success for high-priority messages; missed updates were reconciled upon rejoin via content hashes.

Human Factors

- **Analyst Agreement:** Recommended priorities achieved **$\kappa = 0.62$** (substantial agreement) against senior analyst labels, improving from **$\kappa = 0.41$** in the baseline.
- **Triage Time:** Mean per-IOC triage time decreased by **27%** with AI-suggested context snippets and ATT&CK mappings.

Interpretation: The combined AI + decentralized approach yielded **faster, higher-quality, and privacy-preserving** sharing. The residual gap between federated and centralized performance is acceptable given the privacy gains. Robustness defenses substantially mitigated poisoning, though targeted attacks against quality scoring remain a research frontier.

CONCLUSION

This manuscript presented a comprehensive architecture and methodology for AI-based threat intelligence sharing on decentralized networks. We argued that the longstanding friction points—privacy, trust, timeliness, and duplication—arise from structural features of centralized sharing and manual curation. Our approach integrates AI-native extraction, correlation, and quality scoring with a decentralized substrate that supplies identity, provenance, policy enforcement, and incentive-compatible governance. Privacy-preserving collaboration (federated learning with secure aggregation and differential privacy, plus PSI for overlap checks) enables collective detection without raw data exchange. Smart contracts encode community rules, manage reputation and slashing, and ensure tamper-evident lineages for every artifact shared.

A proof-of-concept evaluation shows promising gains in detection F1, MTTD, deduplication, and analyst productivity, while maintaining acceptable latency and resilience. Importantly, the design preserves compatibility with existing ecosystems through STIX/TAXII and MISP/OpenCTI connectors, easing adoption by ISACs/ISAOs and sector coalitions.

Limitations include (i) dependence on high-quality identity vetting to prevent sybil infiltration, (ii) the need for careful parameterization of DP to balance privacy and utility, (iii) engineering overhead for connectors and schema evolution, and (iv) the open challenge of adversarial pressures on reputation mechanisms (gaming upvotes, coordinated brigading). Future work should explore (a) adaptive, context-aware DP budgets for periods of elevated threat, (b) end-to-end cryptographic attestations of model inference pipelines, (c) automated policy compliance proofs using zero-knowledge techniques, and (d) socio-technical governance playbooks for mixed public–private consortia. With these advances, decentralized, AI-native CTI sharing can transform the threat landscape from fragmented defense toward collective resilience.

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